ERDC/CHL TR-21-10

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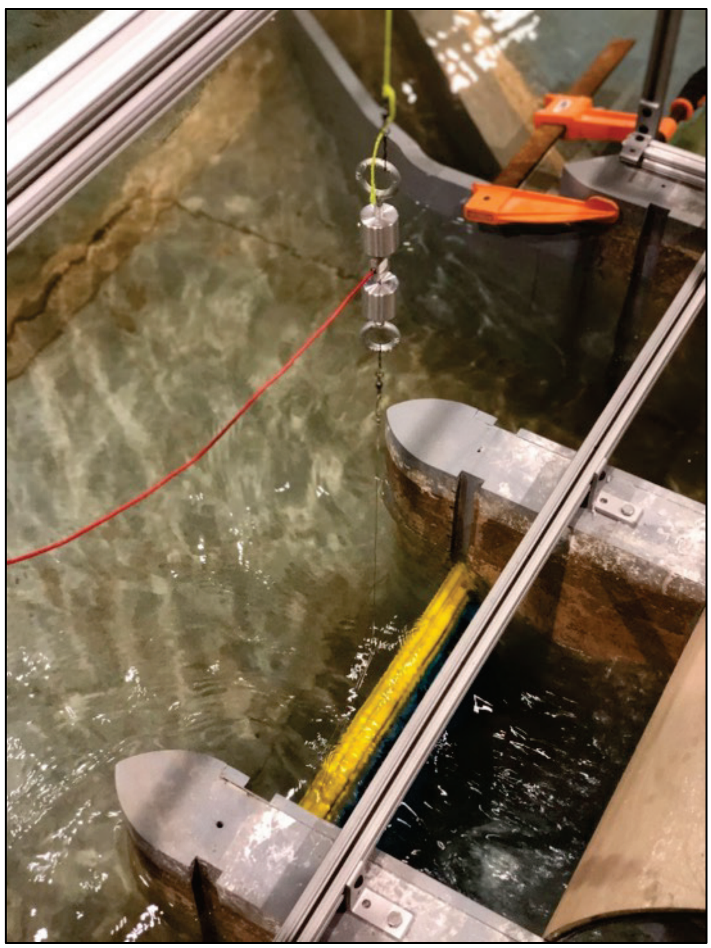
Red River Structure Physical Model Study: Bulkhead Testing

Gary L. Bell and Duncan B. Bryant

June 2021



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Final report

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Prepared for US Army Corps of Engineers, St. Paul District
Saint Paul, MN 55101

Under MIPR 3122-20/XX-2429,"Fargo-Moorhead Metropolitan Area Flood Risk Management Project: Red River Structure Physical Model Bulkhead Testing"

Abstract

The US Army Corps of Engineers, St. Paul District, and its non-federal sponsors are designing and constructing a flood risk management project that will reduce the risk of flooding in the Fargo-Moorhead metropolitan area. There is a 30-mile long diversion channel around the west side of the city of Fargo, as well as a staging area that will be formed upstream of a 20-mile long dam (referred to as the Southern Embankment) that collectively includes an earthen embankment with three gated structures: the Diversion Inlet Structure, the Wild Rice River Structure, and the Red River Structure (RRS). A physical model has been constructed and analyzed to assess the hydraulic conditions near and at the RRS for verification of the structure's flow capacity as well as optimization of design features for the structure. This report describes the modeling techniques and instrumentation used in the investigation and details the evaluation of the forces exerted on the proposed bulkheads during emergency operations for the RRS.

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Preface

This study was conducted for the US Army Engineer District, St. Paul (MVP), under project identification “Fargo-Moorhead Metropolitan Area Flood Risk Management Project: Red River Structure Physical Model Study,” MIPR 3122-20/XX-2429. The technical monitor for MVP was Mr. Duane Perkins, structural engineer.

The work was performed by the River and Estuarine Engineering Branch of the Flood and Storm Protection Division, US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL). At the time of publication of this report, Mr. David P. May was Branch Chief; Dr. Cary A. Talbot was Division Chief; and Dr. Julie D. Rosati was the Technical Director for the Flood & Coastal Risk Management Research and Development. The Deputy Director of ERDC-CHL was Mr. Keith Flowers, and Dr. Ty V. Wamsley was the Director.

The Directorate of Public Works personnel constructed the model as well as the bulkheads. At the time of construction and bulkhead fabrication, Mr. Zachary Smith was the Model Shop Supervisor, and Mr. Mickey Blackmon was the Project Manager.

The Commander of ERDC was COL Teresa A. Schlosser, and the Director was Dr. David W. Pittman.

1 Introduction

The efforts by the US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, to construct segmented bulkheads and assess their performance and operation in the 1:40 scaled Red River Structure (RRS) general model are described in this report. The RRS is one of three gated structures along the proposed dam of the Fargo-Moorhead Metropolitan (FMM) Area Flood Risk Management Project. The dam, known as the Southern Embankment since it is located south of the metropolitan area, will store water when the inflow exceeds 21,000 cfs*, which corresponds to a 1/20 annual exceedance probability (AEP) flood event based on current hydrology. The AEP was computed by US Army Corps of Engineers (USACE), St. Paul District (MVP). In addition to the RRS, two other gated structures will be located along the Southern Embankment. These gated structures are the Wild Rice River Structure (WRRS) and the Diversion Inlet Structure (DIS) (see Figure 1 for a project overview map). Bell et al. (2020) provide more information related to the FMM Area Flood Risk Management Project.

The WRRS and DIS have completed the design phases and have broken ground on construction. The RRS remains in the design phase. The RRS, WRRS, and the DIS are designed to collectively pass the Probable Maximum Flood (PMF) while maintaining a headwater elevation of no more than 923.5 ft just upstream of the RRS (refer to Bell et al. [2020] for datum information). The RRS is the largest of the gated structures and is required to pass more flow than the WRRS and DIS combined during the PMF. Thus, the implementation of an undistorted free-surface 1:40 Froude-scaled general physical model was deployed to evaluate the capacity potential of the RRS and the efficiency of various design considerations (Bell et al. 2020). The physical model also evaluated the energy dissipation capability of the RRS design to understand erosive potential near the structure. The final design from that study was used for the bulkhead testing presented in this report.

* For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

Figure 1. FMM Area Flood Risk Management Project overview.

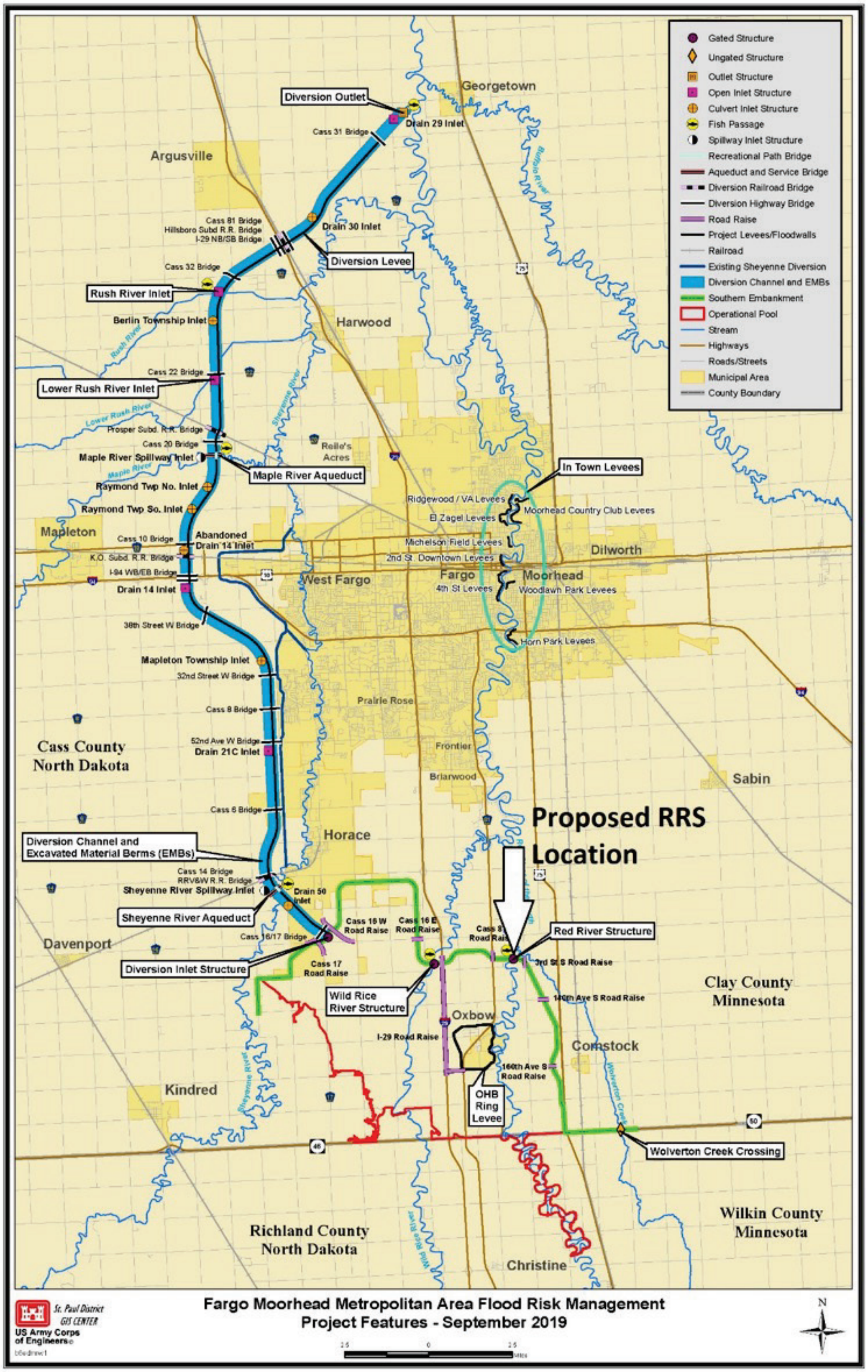


Table 1 lists L_r conversions relevant to the physical model. All data presented in this report are at prototype scale unless otherwise specified.

Table 1. Physical model scale conversions.

Variable	Froudian Similitude Scale	Scale Relation Model:Prototype
Length	L_r	1:40
Velocity	L_r^0.5	1:6.32
Discharge	L_r^2.5	1:10,119
Mass	L_r^3	1:64,000
Force	L_r^3	1:64,000

1.1 Background

The FMM area has a history of high floodwaters. The years 1997, 2009, and 2011 are three examples of large flood events. The RRS, combined with the WRRS, DIS, and Southern Embankment, is intended to provide protection for more than 230,000 people in the FFM area during periods of flooding. The RRS proposed location is approximately 10 miles south of the FMM area on the Red River, between Interstate 29 and US Highway 75, to the west and east, respectively. The location of these structures can be seen in Figure 2 (the black line represents the Southern Embankment). The final design features that will be included for the bulkhead testing are shown in Figure 3 and Figure 4.

Figure 2. Gated structure locations.

Figure 3. Final upstream design features.

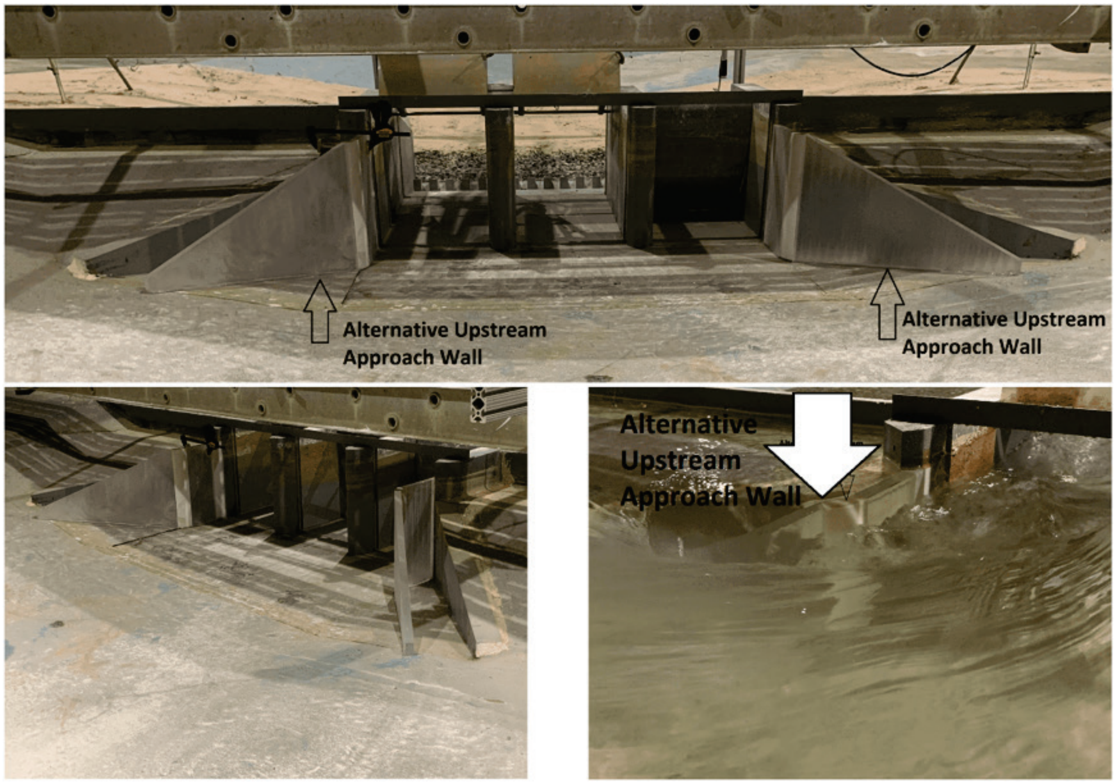
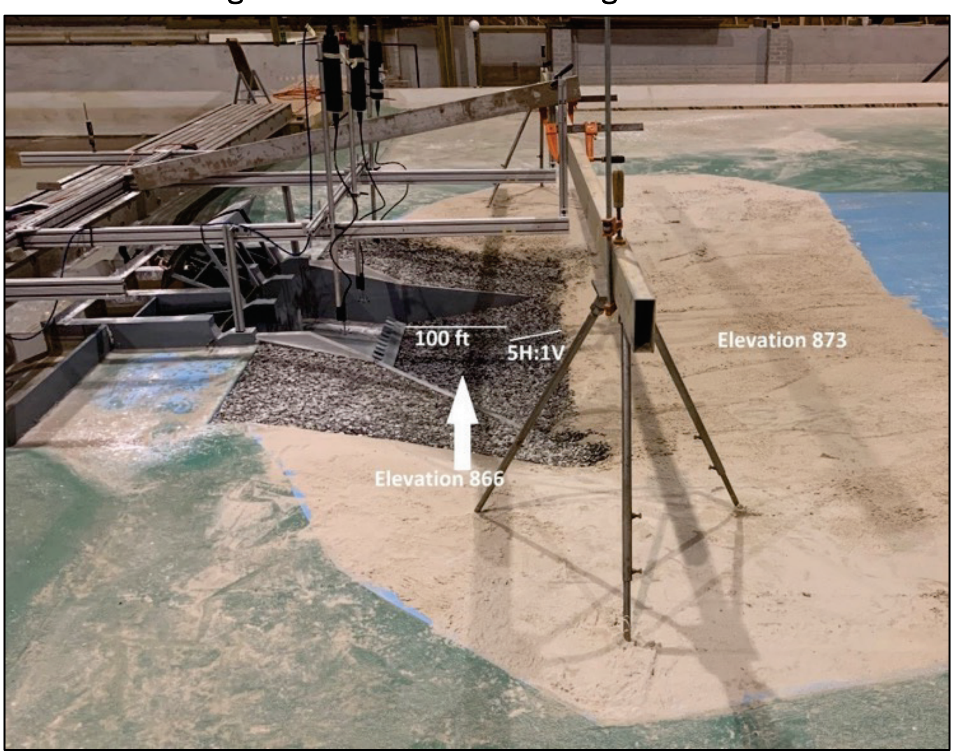


Figure 4. Final downstream design features.

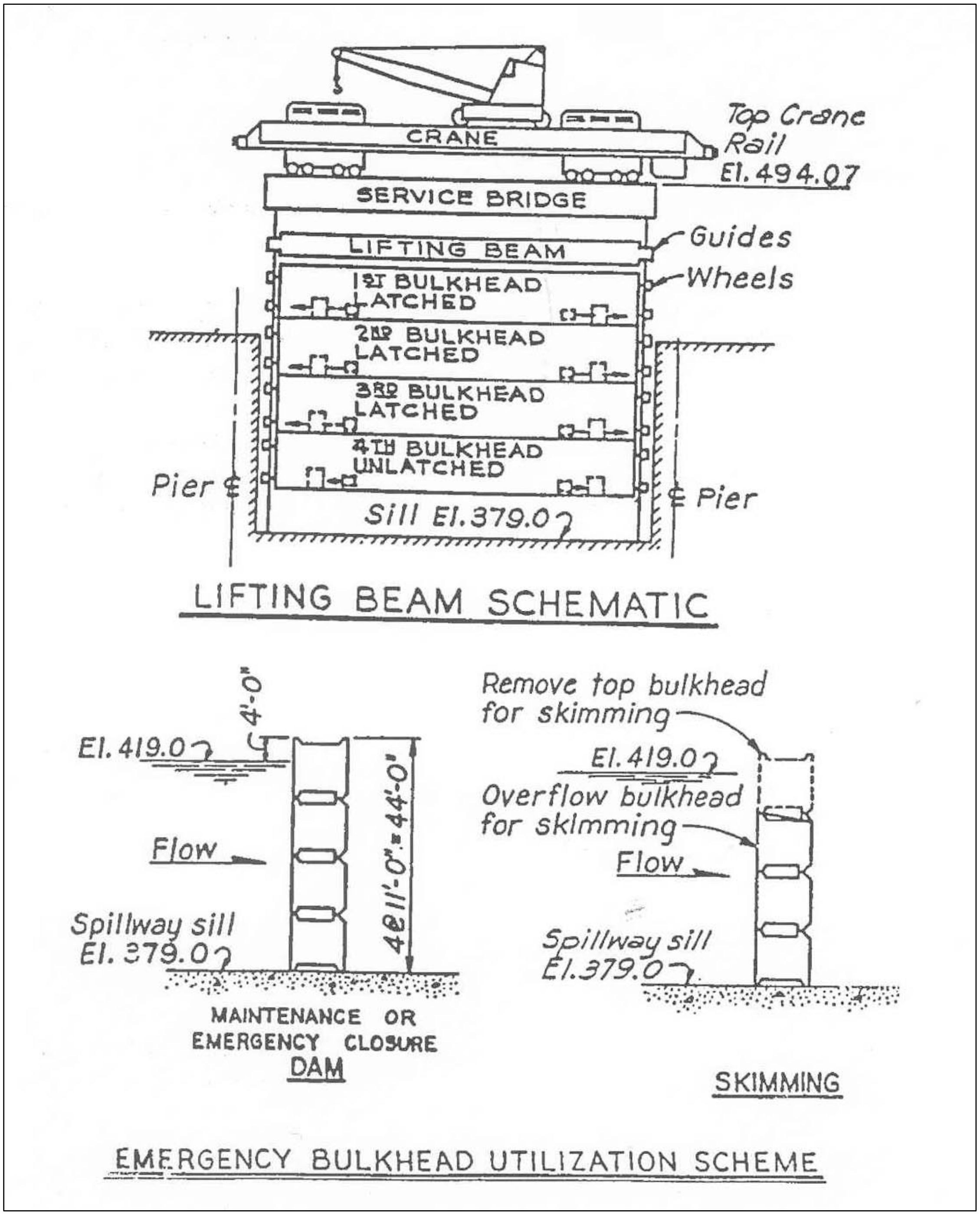


Bulkheads are typically steel structures, and stop logs are usually wooden beams; however, the two terms are used interchangeably to describe structures used to block the flow of water (HQ USACE 1987). Lewin (1995) states that emergency closure gates, a type of bulkhead, cannot be placed (placed rapidly in flowing water under a head differential) as individual or segmented units in flowing water because they are subject to vibration from combined flow over and under the section. Although Lewin (1995) suggests that individual sections cannot be placed one at a time, model studies and a prototype test have shown that this method of deployment can be used successfully (Maynord and Stockstill 2012).

The following is from Hite (2008):

“Most Corps projects have temporary bulkheads or closure structures for unwatering during maintenance activities. These structures are generally stored onsite or at a central location so they can be used at several projects. Cranes, stiffleg derricks, derrick boats, and divers are used for installation. These structures are generally installed in a static pool. Figure 5 from Headquarters, US Army Corps of Engineers (1995a) shows a bulkhead closure system typically used in a static pool. If this system is used with flowing water, the lowering carriage and bulkheads are lowered slowly down the bulkhead slot and the flowing water does not pass over the bulkheads. Other types of emergency closure bulkheads that stop the flow of water through the lock or dam are available at a few projects. These existing emergency closure structures typically include sectional bulkheads and vertical lift gates (overhead or submerged) which can be installed in flowing water. HQ USACE (1995b) indicates no universally accepted definition of emergency closure exists. The required action is generally understood to be that a closure structure must be rapidly placed in flowing water under head differential.”

Figure 5. Typical emergency bulkhead closure system from EM 1110-2-2602 (HQ USACE 1995a).



1.2 Objective

The objective of this effort is to provide MVP with physical model data representing the hydrodynamic loads that will be produced from lowering bulkheads into position during emergency operations.

1.3 Approach

The existing RRS physical model (Bell et al. 2020) will be used with no changes made to the model to collect data for several varying flow conditions. The hydrodynamic loads exerted on the bulkhead during physical model testing will be collected using a load cell. Load data will be presented in terms of total hydrodynamic loading exerted on the bulkhead (either uplift or downpull).

1.4 US Army Corps of Engineers (USACE) guidance

Maynord and Stockstill (2012) give the following regarding USACE guidance on stacked bulkheads and vertical-lift gates for emergency closures:

"Engineering manual EM 1110-2-2607, Planning and Design of Navigation Dams (HQ USACE 1995), states that the USACE has primarily used stacked bulkheads and vertical-lift gates for emergency closures. The stacked bulkhead arrangement has proven to be the most dependable and reliable for emergency closure purposes."

The bulkheads have end rollers and are usually of the open truss design with skin plate on the upstream side.

EM 1110-2-2607, *Planning and Design of Navigation Dams* (HQ USACE 1995), notes that several cases of barge collisions have resulted in barges becoming lodged at the bulkhead gate location and have precluded installation of emergency closure gates. The "Lessons Learned – Case Histories" in Appendix C of EM 1110-2-2607 documents the seriousness of barges blocking and sinking upstream of navigation dams.

EM 1110-2-2607 states "Past experience and model testing by WES have shown that bulkheads cannot be lowered safely one at a time in flowing water. Therefore, the stacked bulkhead system was developed so that the flowing water never goes over the top of the bulkheads." EM 1110-2-2607 also states that placement of emergency closure bulkheads can be accomplished from a floating plant, which is contrary to Lewin's (1995) recommendation that a rail-mounted gantry crane can be used.

EM 1110-2-1604, Hydraulic Design of Locks (HQ USACE 2006), states that the most common type of emergency closure gate is a bulkhead consisting of one or more sections. The bulkhead uses a watertight skin plate on the upstream side and includes seals and roller assemblies. The vertical height of the bulkhead varies from 3 to 12 ft. EM 1110-2-1604 also notes that most designs do not permit combined flow over and under the gates. The manual describes the placement procedure in which the gates are "dogged" to hold them in position. This is the placement procedure used at Belleville Locks and Dam, which is discussed later in this report.

EM 1110-2-2703, *Lock Gates and Operating Equipment* (HQ USACE 1994), provides details and design loadings for various emergency closure gates. An overview of design load information in EM 110-2-2703 provides the following:

- Hydrodynamic forces on emergency bulkheads can result in uplift and downpull depending on the design.
- Lowering bulkheads in flowing water requires that the uplift force is less than the submerged weight of the bulkhead.
- Design of hoisting machinery requires knowledge of the magnitude of hydraulic downpull.

The following is from ETL 1110-2-2105, *Design of Hydraulic Steel Structures* (HQ USACE 2014):

"G.2.5. Emergency Bulkheads.

G.2.5.1. This term refers to the intended use of a bulkhead rather than to its configuration. Maintenance bulkheads are usually placed in still water with no differential head. Emergency bulkheads are intended for use when there is an unexpected problem with another gate. The bulkhead is installed to prevent excess release of water, which could cause flooding or loss of pool. This might require the emergency bulkhead to be lowered into position in rapidly flowing water. This can cause significant vertical and horizontal forces on the gate while it is being positioned.

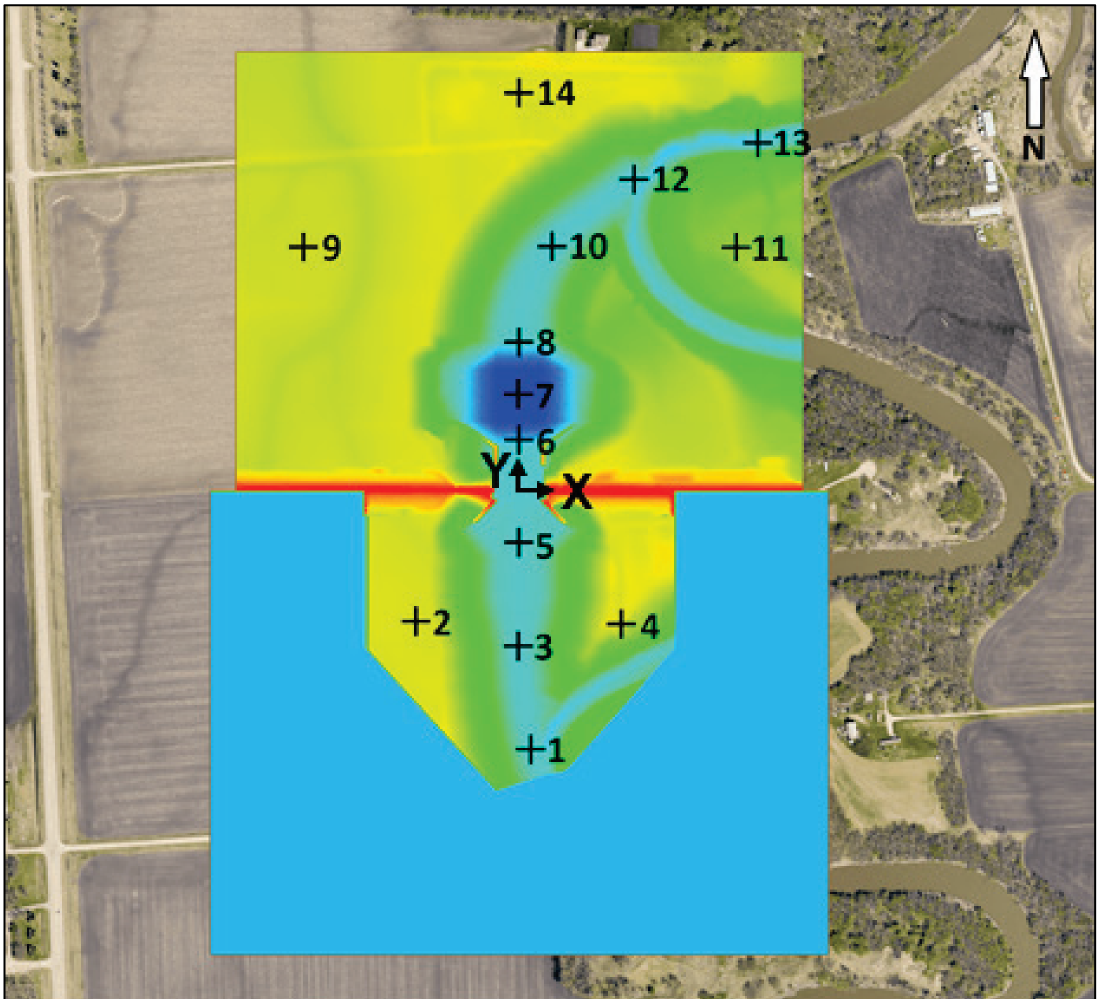
G.2.5.2. Design of emergency bulkheads will be slightly different because of these hydrodynamic forces. The lower lip of the gate must be configured to minimize vertical forces. This is done in consultation with the Hydraulic Engineer. The horizontal forces can cause friction while the bulkhead is moving, thus wheels might be used instead of sliding bearings. If the friction and vertical forces are larger than the weight of the unit, it might be necessary to have equipment that can force the bulkhead down into position. Appendix E includes the design of emergency bulkheads configured as a lift gate."

2 Process and Setup

2.1 Data collection/instrumentation

To monitor and set the discharge rates into the physical model, the flow was measured directly through the supply lines by ultrasonic flowmeters from EESIFLO International. The flow meters accurately measure flow within +/- 2%. Cross-linked polyethylene piping was routed under the graded deck to the 14 gage locations for monitoring water surface elevation (WSE) readings during testing (Figure 6). Note that x = 0 ft at the center of the middle gate opening and y = 0 ft at the centerline of the Southern Embankment. A stilling well station for monitoring the WSEs in the model was set up on the outer support wall attached to the graded deck of the upstream portion of the model (Figure 7). For WSE measurements, a digital point gage was used. The point gages have sub-millimeter accuracy, which translates to accurate prototype-scale WSE measurements to within +/- 0.1 ft. The instruments were referenced to a benchmark (base elevation) on the frame of the stilling well basin. For more information in regard to the physical model setup/construction, refer to Bell et al. (2020).

Figure 6. Model gage locations.



Gage #	X (ft)	Y (ft)
1	50	-1000
2	-400	-510
3	0	-600
4	400	-520
5	0	-200
6	0	200
7	0	370
8	0	570
9	-840	940
10	130	940
11	840	940
12	450	1210
13	930	1340
14	0	1540

Figure 7. Stilling basin gage station.

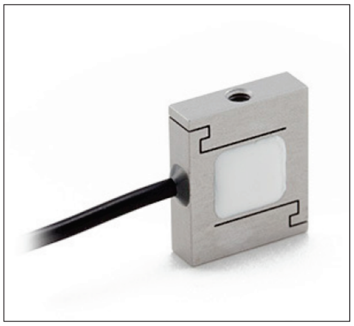
The load data were collected using a Jr. Miniature S-Beam load cell from FUTEK Advanced Sensor Technology, Inc. Technical specifications and calibration data are found in Figure 8 and Figure 9. Excitation voltage and signal amplifications were achieved using a Futek IAA100 analog load cell amplifier. The load cells were delivered from Futek calibrated with their paired amplifiers. Appendix A contains the specific FUTEK calibration data for each of the load cells. An alternate FUTEK load cell was used only for the 50-year event. National Instruments hardware (NI 9202 paired with a cDAQ-9184) were used to collect the voltage output from the load cell amplifier. The National Instruments hardware was controlled through a custom LabVIEW-based program.

Figure 8. FUTEK load cell technical specifications.

FUTEK
ADVANCED SENSOR TECHNOLOGY, INC.

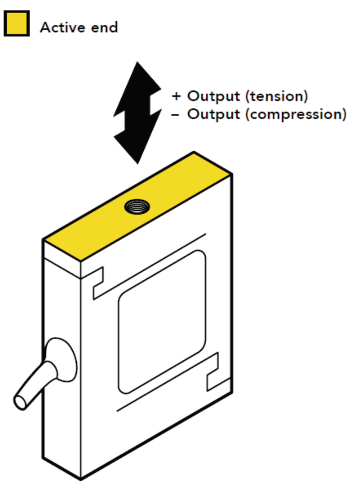
MODEL LSB210

Submersible Jr. Miniature S-Beam Load Cell



FEATURES

- Up to 10 times the overload protection
- Light weight
- Loads up to 100 lb (445 N)
- Miniature size



SPECIFICATIONS	
PERFORMANCE	
Nonlinearity	See chart on next page
Hysteresis	See chart on next page
ELECTRICAL	
Excitation (VDC)	10 max
Bridge Resistance	1000 Ohm nom (100 g), 350 Ohm nom
Insulation Resistance	≥500 MOhm @ 50 VDC
Connection	#29 AWG, 4 conductor, spiral shielded silicone cable, 5 ft [1.5 m] long
Wiring/Connector Code	WC1
MECHANICAL	
Weight (approximate)	0.3 oz [9 g] (100 g–10 lb) 0.9 oz [26 g] (100 lb)
Safe Overload[1]	1000% of RO 200% of RO tension only (100 lb)
Material	Anodized aluminum (100 g–10 lb), 17-4 PH stainless-steel (100 lb)
IP Rating	IP68
Water Resistance	Up to 50 ft in fresh water for less than one week
TEMPERATURE	
Operating Temperature	0 to 160°F [-17 to 72°C]
Compensated Temperature	60 to 160°F [15 to 72°C]
Temperature Shift Zero	±0.02% of RO/°F [0.04% of RO/°C]
Temperature Shift Span	±0.04% of Load/°F [0.08% of Load/°C]
CALIBRATION	
Calibration Test Excitation	5 VDC
Calibration (standard)	5-pt Tension
Calibration (available)	Compression
Shunt Calibration Value	60.4 kOhm, 301 kOhm (100 g)
CONFORMITY	
RoHS	2011/65/EU
CE	EN61326-1:2006

[1]Sensor structure can handle high overloads but threads may limit overload at higher capacity

Sensor Solution Source
Load · Torque · Pressure · Multi-Axis · Calibration · Instruments · Software
www.futek.com

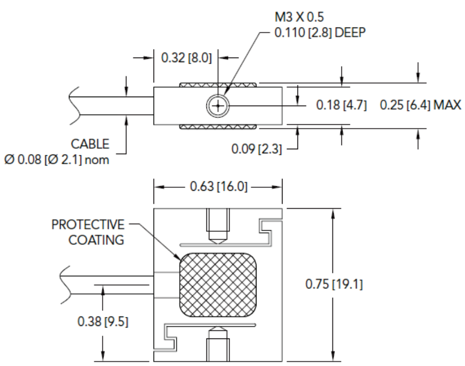
CE RoHS ANSI Z540-1 ISO 17025 ISO 9001 ISO 13485 U.S. Manufacturer

Figure 9. FUTEK load cell technical specifications.

Model LSB210

2

DIMENSIONS inches [mm]



CAPACITIES

ITEM #	lb	N	RO (nom)	Non-Linearity	Hysteresis	Zero Return	Creep 10 mins
FSH03940	100 g	1	1 mV/V	3% RO	5% RO	3% RO	12% RO
FSH03941	2	8.9	2 mV/V	0.5% RO	1% RO	0.5% RO	1% RO
FSH03942	10	44.5	2 mV/V	0.2% RO	0.2% RO	0.2% RO	0.5% RO
FSH03943	100	445	2 mV/V	0.2% RO	0.2% RO	0.2% RO	0.2% RO

WIRING CODE (WC1)

RED	+ EXCITATION
BLACK	– EXCITATION
GREEN	+ SIGNAL
WHITE	– SIGNAL
SHIELD	FLOATING

Drawing Number: FI1318-D

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2.2 Boundary conditions and model operation

Three potential boundary conditions outlined in Table 2 were tested in the physical model. For in-bank flow conditions, gage 13 was used as the tailwater control. For out-of-bank flow conditions, gages 9, 11, 13, and 14 were used as the tailwater control. All three radial tainter gates are completely open for the PMF conditions; thus, the headwater elevation is uncontrolled (Bell et al. [2020] provide a detailed description of the RRS). Bulkhead load data were collected only for the center gate throughout testing, and the center tainter gate was always completely open. The maximum headwater elevation of 921 ft was not exceeded in the physical model; thus, there were no discharge adjustments made during testing. For more information regarding the physical model's control boundaries, refer to Bell et al. (2020).

Table 2. Boundary condition data.

Event	RRS Discharge (cfs)	Maximum Headwater Elevation (ft)	Tailwater Elevation (ft)	East Gate	West Gate
20-year Event	10,700	*	910.1	Open	Open
20-year Event	12,400	921.0	909.9	Closed	Closed
50-year Event	29,000	*	912.2	Open	Open
PMF	104,300	*	917.5	Open	Open

* To be determined using the physical model.

2.3 Model bulkhead design and fabrication

The first step in the bulkhead construction process was to take the initial bulkhead design and create a three-dimensional (3D) drawing in AutoCAD. The drawing was developed by the Philadelphia District as well as the MVP (Figure 10). Note that this design drawing has the lifting beam attached to the bulkhead. The lifting beam/bulkhead will stay attached to the load cell for the duration of physical model testing. The remaining bulkheads will be printed without the lifting beam so that they can be put into place as needed throughout testing. The bulkheads are 54 ft long, 2.25 ft wide, and 3.75 ft tall. The lifting beam is 1 ft tall. The drawing was scaled to model scale and exported to be printed by a Stratasys J750 3D printer (Figure 11).

Figure 10. Initial bulkhead design (3D drawing looking upstream on the top, 3D drawing looking downstream on the lower left, and a similar proposed bulkhead design in prototype on the lower right).

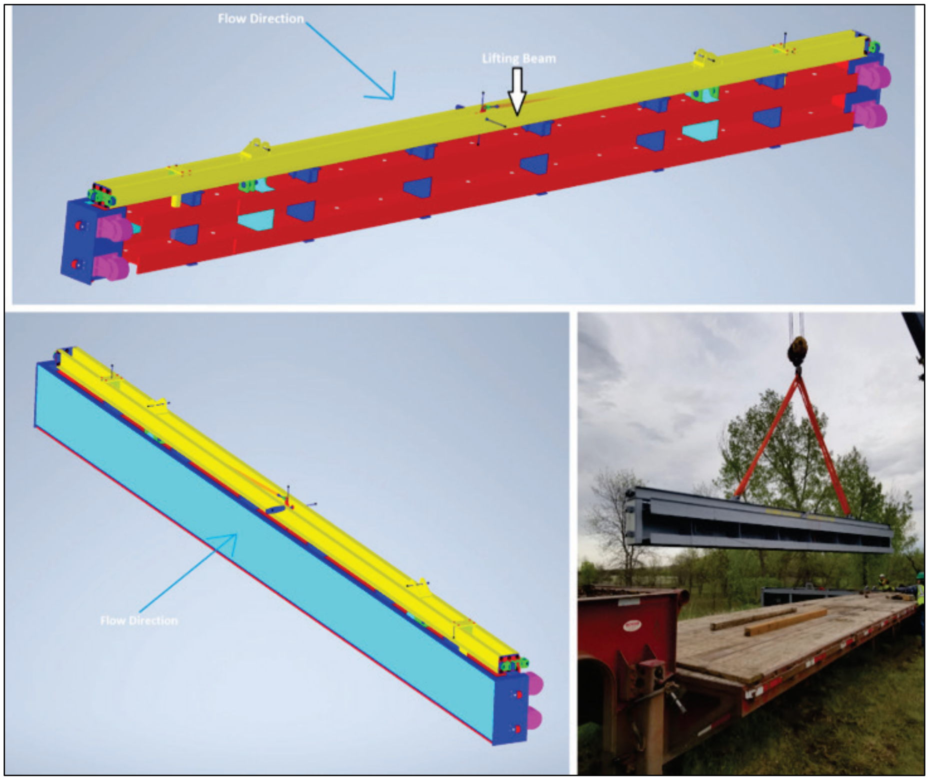
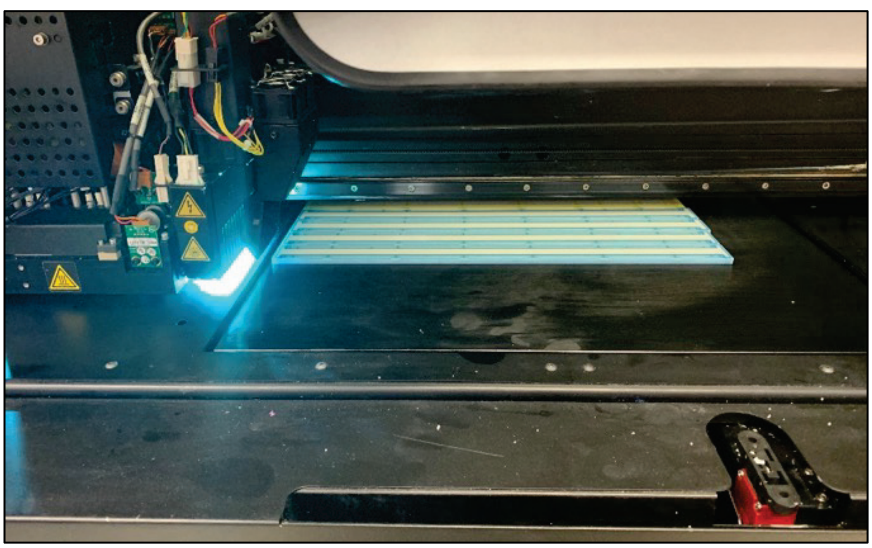
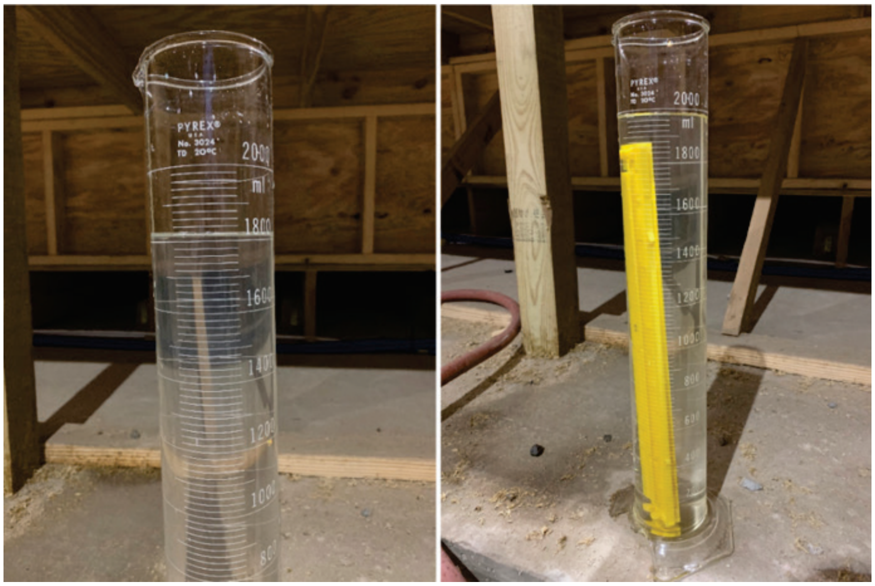


Figure 11. Stratasys J750 3D printer during the bulkhead 3D printing process.



After the bulkheads were printed, they were measured to determine their volume. This was done by placing water in a graduated cylinder and recording the initial volume; for this test it was 1,820 ml or approximately 61.5 US fluid oz. The bulkhead (with the lifting beam attached) was then fully submerged, and the final volume was 67.12 oz, which leads to a bulkhead volume of 5.58 oz at model scale. Figure 12 shows the initial volume on the left and the final volume on the right.

Figure 12. Bulkhead volume measurement.



With the measured volume at model scale, the volume of the proposed prototype bulkhead can be estimated. The estimated weight of the lifting beam and bulkhead is 5,000 lb and 26,000 lb, (respectively) totaling 31,000 lb. Dividing this weight by the density of carbon steel (490.752 lb/ft^3), the total volume of the prototype bulkhead and lifting beam is calculated to be 63.2 ft^3. Next, the buoyant force that is expected to be exerted on the bulkhead/lifting beam combination is found by multiplying the volume, density of water, and gravitational constant (g). This leads to a total net load, weight of bulkhead and lifting beam minus the buoyant force, of 27,053 lb in prototype. The total net load of the model lifting beam and bulkhead scaled up to prototype was 22,170 lb. Additional weight was added to the bulkhead/lifting beam combination such that the submerged weight in the model equaled that in prototype. This was important as a model bulkhead whose submerged weight differed from the prototype could respond differently to an applied hydrodynamic force. The weights were added to the model bulkhead at locations where the center of gravity for the model bulkhead would be similar to the center of gravity for the prototype bulkhead. Figure 13 displays the testing configuration. The added weights are circled in red on the left image in the figure.

Figure 13. Bulkhead testing set-up (left image is looking upstream; right image is looking downstream).

3 Physical Model Results

3.1 Testing procedure

In past studies such as Hite and Pickering (1983), it was found that the vertical hydrodynamic force could vary significantly from uplift to downpull when there is a differential head across the structure. It also concluded that the forces acting on the bulkhead become unpredictable as the nappe overtops the bulkhead and as the nappe overtops the lifting beam. These effects combined with a varying tailwater are conducive to situations where the bulkhead is subject to violent uplift and downpull movements at certain positions in the water column.

For each data set collected from the physical model, the bulkhead was lowered in increments of approximately 1.7 ft (1/2 in. model scale) or approximately 3.3 ft (1 in. model scale), and hydrodynamic load data were collected at static positions in the water column until the bulkhead reached either the structure bottom or the last placed bulkhead. For conditions that were calm (i.e., little to no vertical movement of the bulkhead during data collection) the FUTEK load cell collected data for approximately 10.5 min (100 sec model scale) at 100 Hz. It was found that at these less turbulent conditions, a sampling frequency of 100 Hz was sufficient to capture the maximum and minimum values of the load data during testing. At more turbulent flow conditions with higher velocities and violent bulkhead movement, a sample frequency of 1,000 Hz was used to adequately capture the peaks and troughs of the fluctuating data (again taken for ~ 10.5 min prototype scale). WSE and discharge data were taken for each test to monitor boundary condition data.

The design team from the MVP and Philadelphia Districts estimated an initial maximum allowable total load of 40,000 lb (40 kips). This is the maximum load that can be handled by the crane during bulkhead placement/operation.

3.2 Results

3.2.1 20-year event

The lowest flow condition that was simulated in the physical model was the 20-year event (refer to Table 2 for boundary condition data). Two scenarios were considered for the 20-year event: one with the east and west gates completely closed and the middle gate completely open while the other scenario considered all three gates completely open. The bulkheads were lowered via the slots in the middle gate piers in increments of approximately 1.7 ft. Bulkheads were lowered until a total of six bulkheads were in place, including the test bulkhead, for both scenarios.

Figure 14 and Figure 15 depict a snapshot looking downstream of the test bulkhead being lowered (yellow) with five bulkheads in place (blue). The top of the lifting beam is at an elevation of 908.2 ft. For the 20-year event east and west gates closed test, the average discharge throughout the testing was 12,300 cfs, and the initial/final WSE for each gage are given in Figure 16. Note that for the final WSE values, there are six bulkheads in place. For the 20-year event all gates open test, the average discharge throughout the testing was 10,760 cfs, and the average WSE for each gage can be seen in Figure 17. Note that gages that do not have data are dry (flow is in-bank only) and flow is from south to north. Gages 8 and 9 are in the channel but have been covered with sand/cement from the testing procedures resulting from Bell et al. (2020) and thus are unavailable for WSE measurements. Reported WSE values are averaged from several sets of measurements over the course of testing for the scenario with all gates open because there was little to no change in the WSE measurements resulting from the placement of bulkheads. This was especially true for the headwater WSE shown in Figure 17. When the east and west gates are closed and six bulkheads are in position, the headwater increases approximately 5 ft (Figure 16) in comparison with all of the gates open and six bulkheads are in place.

Figure 14. The 20-year event test (east and west gates closed).

Figure 15. The 20-year event test (all gates open).

Figure 16. The 20-year event (east and west gates closed) initial (left) and final (right) WSEs (feet).

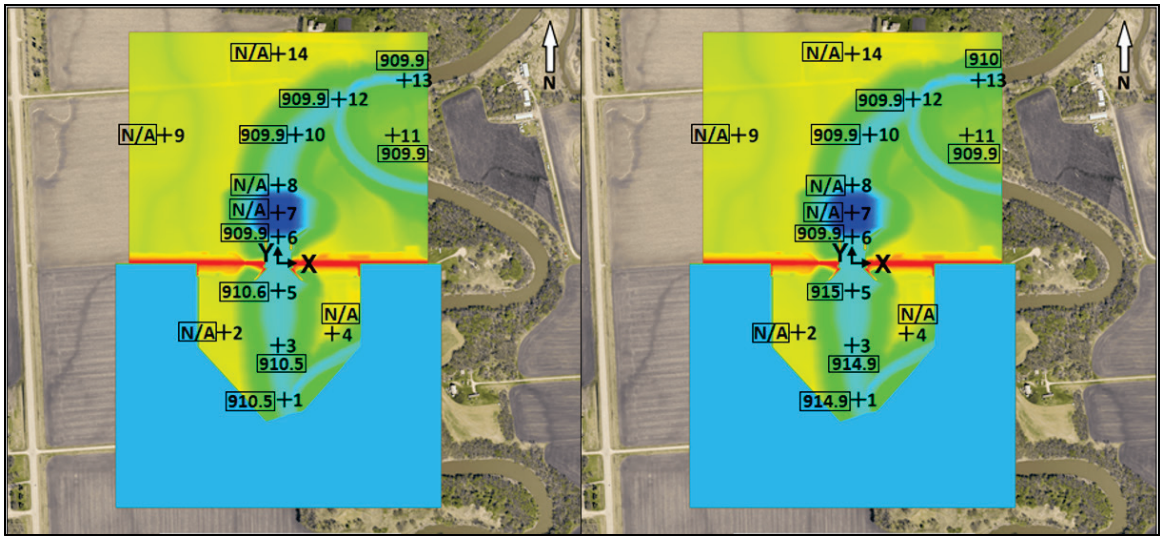
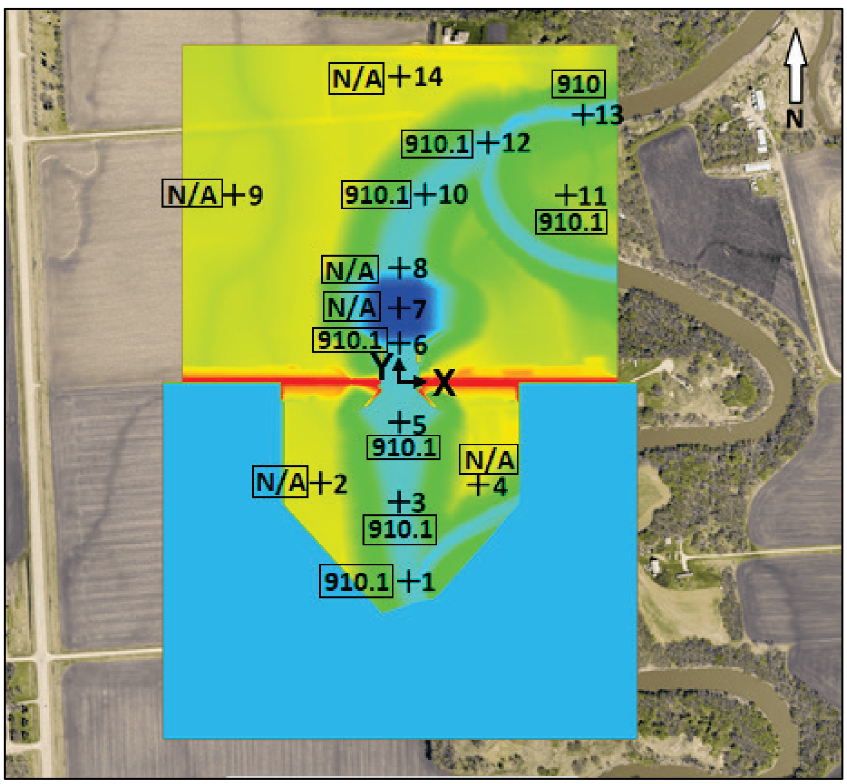


Figure 17. The 20-year event (all gates open) average WSEs (feet).



For each test, the total load was measured as uplift or downpull. Figure 18 through Figure 20 display the test data for the placement of the first three bulkheads for the 20-year event east and west gates closed scenario. The bulkhead position represents the top elevation of the lifting beam. Note that in each figure, the bulkhead and lifting beam combined weight is plotted as a horizontal red line and the buoyancy force of the bulkhead/lifting beam is plotted by a horizontal blue dashed line for reference and the error bars provide the maximum and minimum forces measured. Figure 18 shows the data with the test bulkhead only. The plots for the fourth through sixth bulkhead placement loadings are shown in Appendix B. Figure 21 displays the average hydrodynamic force for the east and west gates closed scenario. As the number of bulkheads in place increases, the head differential also increases since the discharge remains constant and the effective flow area is reduced by the presence of the bulkheads. The largest force fluctuations were measured with two bulkheads on the bottom and the test bulkhead and lifting beam between elevations 900 to 905 as shown in Figure 20. Once three or more bulkheads were sitting on the bottom (Figures 57 – 59), the force fluctuations were significantly reduced. This indicates a much more stable flow control with these conditions.

Figure 22 through Figure 24 show plots of the test data from zero bulkheads in place to two bulkheads in place for the 20-year event with all gates completely open. Figure 25 plots the average hydrodynamic force for the all gates open scenario. The force fluctuations were minimal with these conditions and there was essentially no vertical hydraulic force on the bulkhead and lifting beam. The hydraulic conditions were much calmer with the 20-year event and all gates open compared to the 20-year event with the east and west gates closed.

The head differential through the structure is one of the contributing factors to the increased loading on the bulkheads for the east and west gates closed scenario compared to the all gates open test. Furthermore, the head differential likely contributes to the vertical movement experienced by the bulkhead when the east and west gates are closed. One difficulty in interpreting the data was the often-higher mean loads measured as the bulkhead entered the water. When the bulkhead first touches the water, all the flow goes underneath, but there is considerable flow separation. Eventually, as the bulkhead is lowered farther, water begins to flow over the top of the bulkhead. However, the combination of flow separation below the bulkhead and lack of mass over the top of the bulkhead results in a bulkhead that is partially submerged. This creates uncertainty in the calculated average hydrodynamic force, and under these conditions the fluctuating forces are the cause for concern.

Figure 18. First bulkhead 20-year event (east and west gates closed) vertical hydraulic forces.

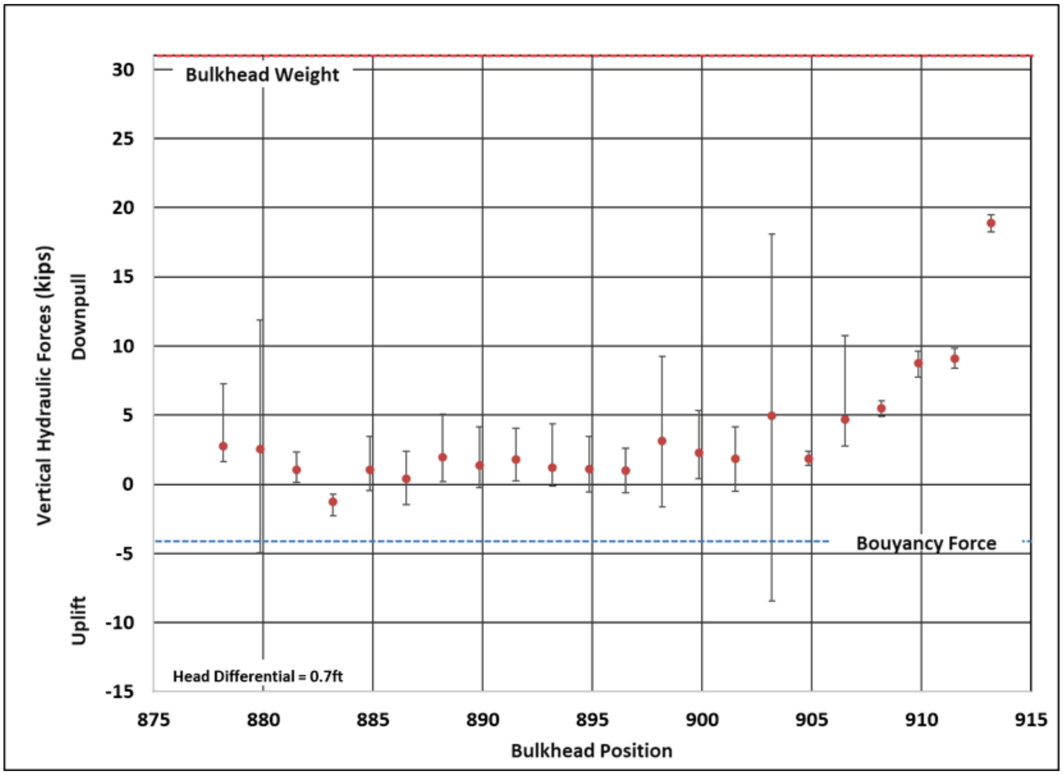


Figure 19. Second bulkhead 20-year event (east and west gates closed) vertical hydraulic forces.

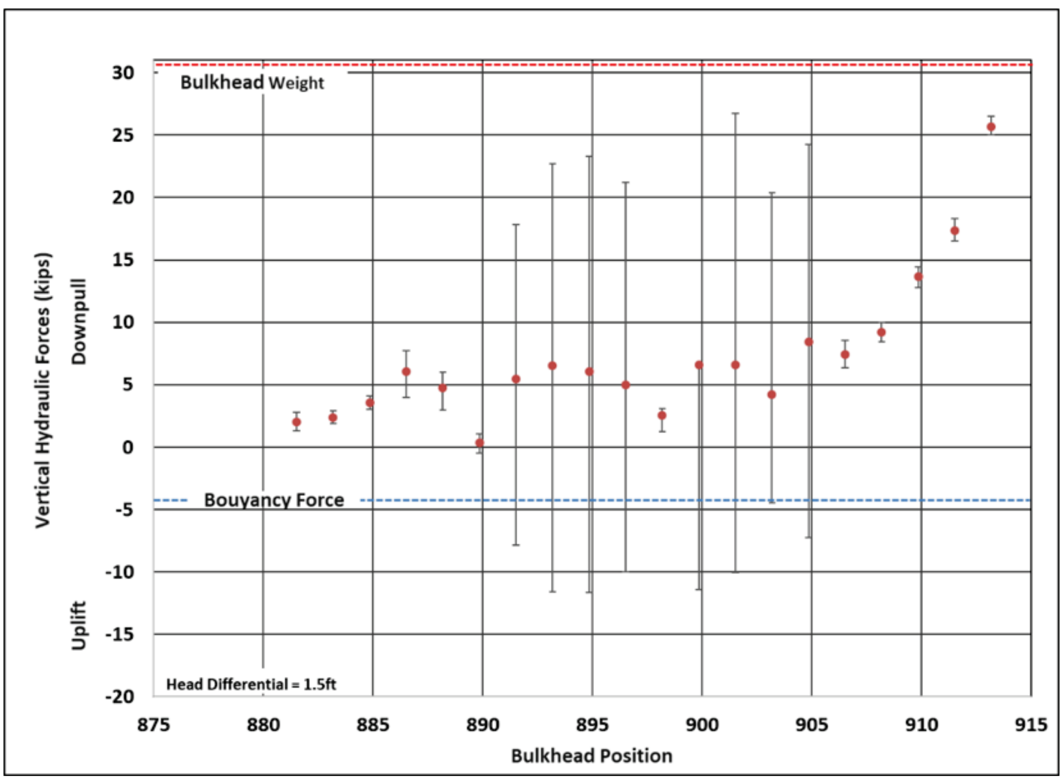


Figure 20. Third bulkhead 20-year event (east and west gates closed) vertical hydraulic forces.

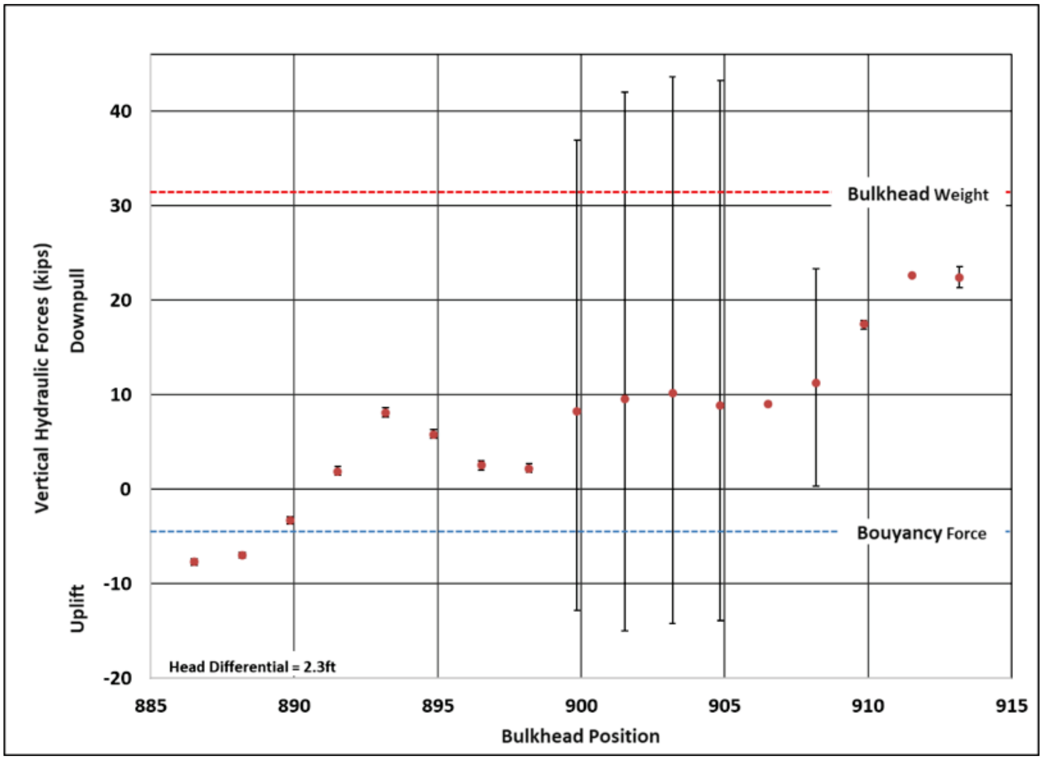


Figure 21. Average hydrodynamic force for all tests 20-year event (east and west gates closed) vertical hydraulic forces.

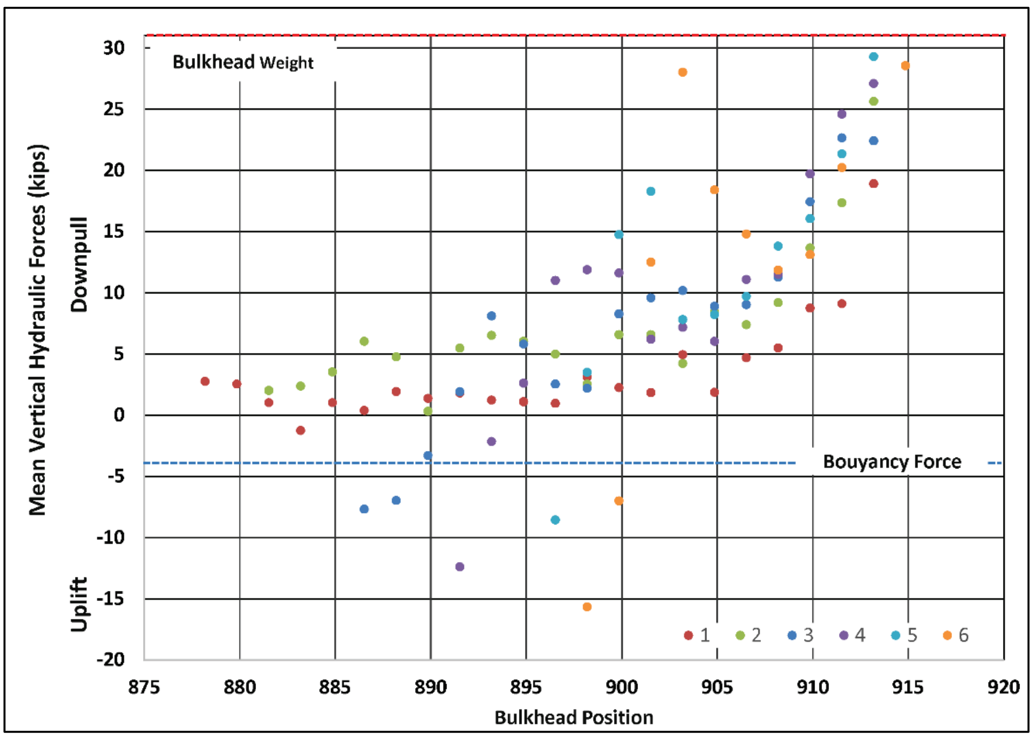


Figure 22. First bulkhead 20-year event (all gates open) vertical hydraulic forces.

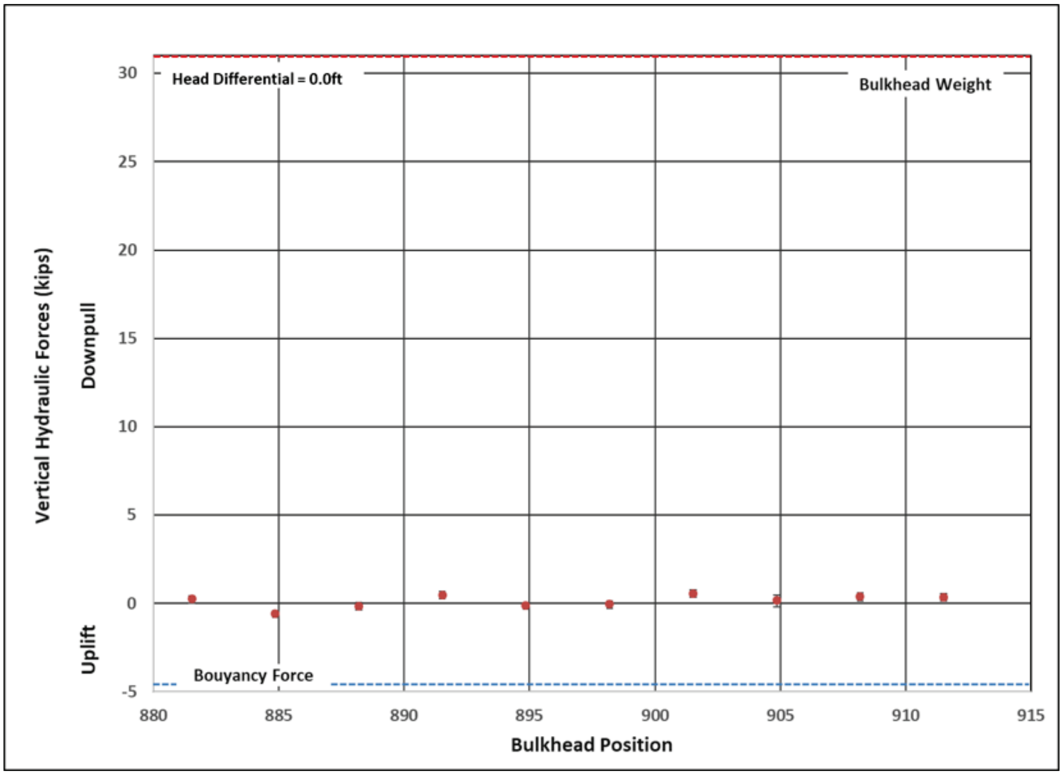


Figure 23. Second bulkhead 20-year event (all gates open) vertical hydraulic forces.

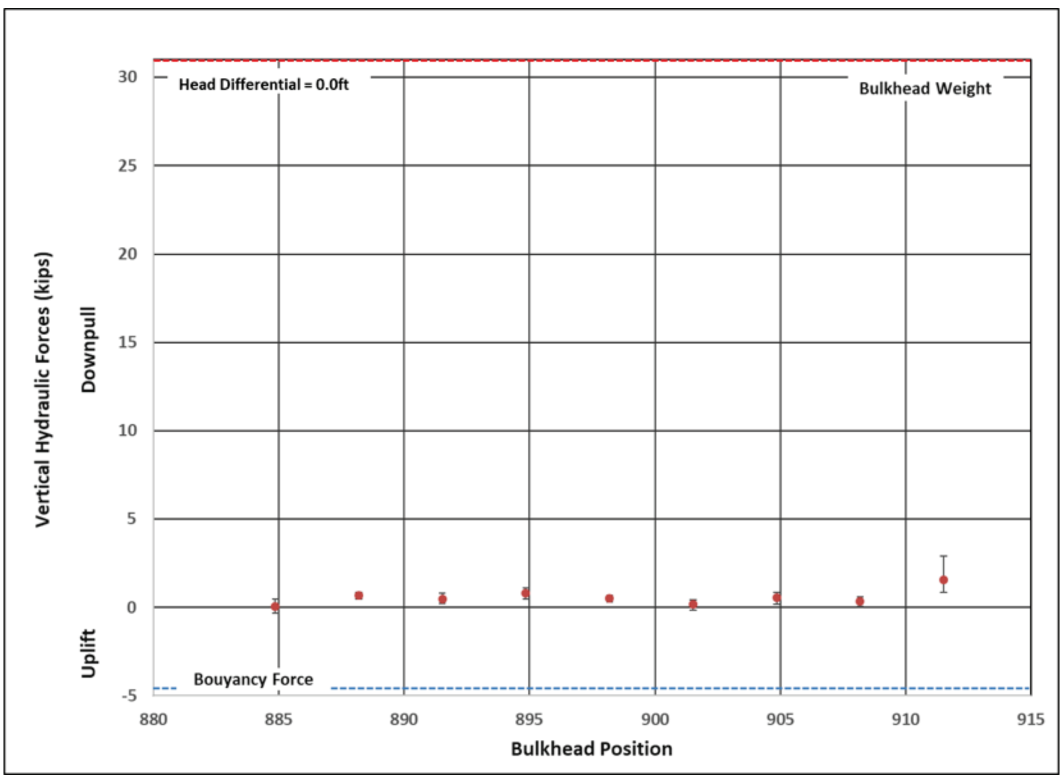


Figure 24. Third bulkhead 20-year event (all gates open) vertical hydraulic forces.

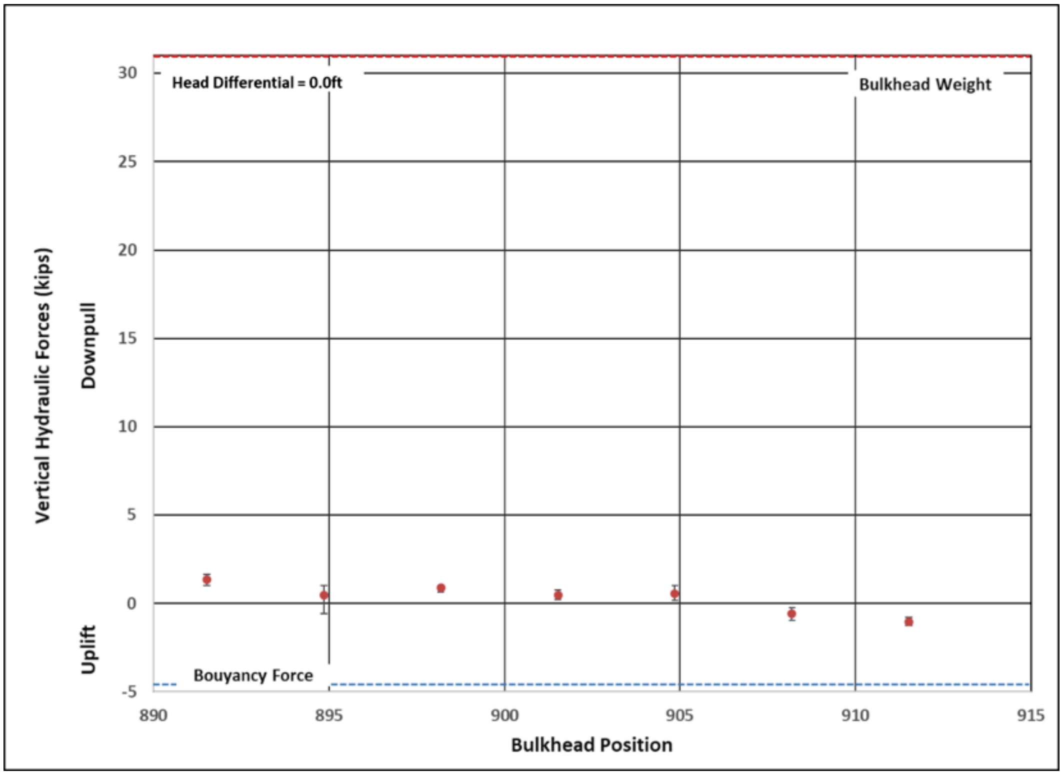
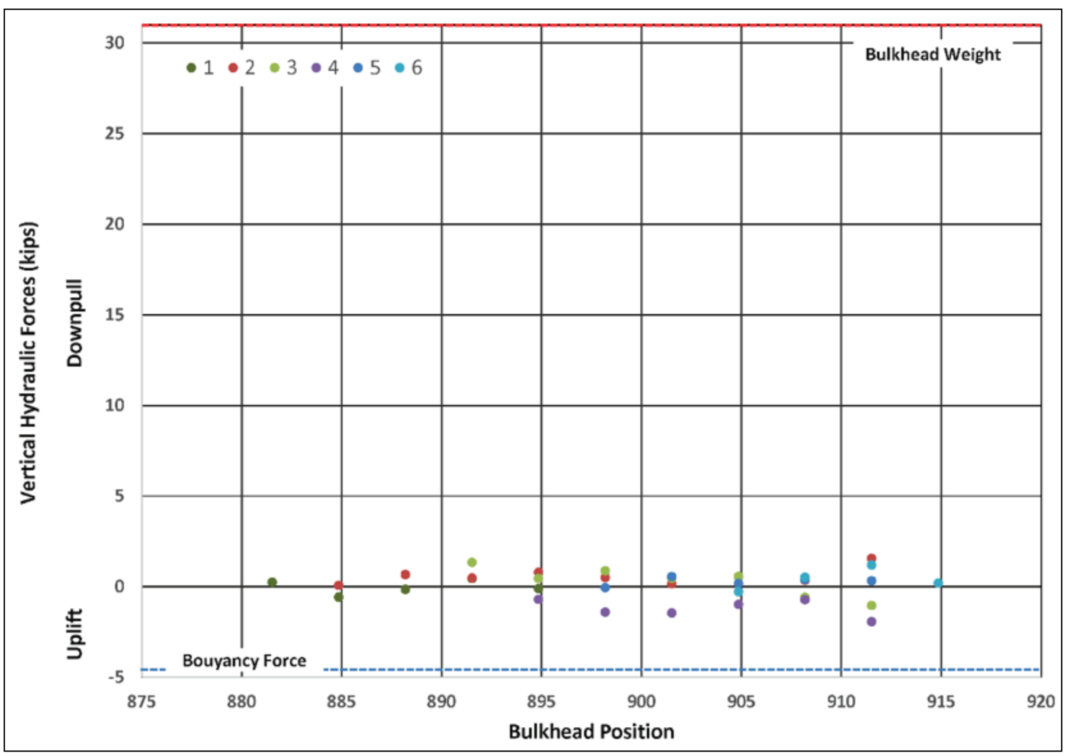


Figure 25. Average hydrodynamic forces for the bulkheads 20-year event (all gates open).



3.2.2 50-year event

The second set of boundary conditions deployed for bulkhead testing was the 50-year event with all gates completely open. Initial attempts were made to test the bulkheads with the east and west gates closed, but extremely violent vertical movement of the bulkhead during the first bulkhead placement resulted in no further testing for that condition. Appendix C displays the data that were collected during that test (note the downpull forces reaching the 145 – 150 kip range). Thus, the all-gates-open scenario load data were collected using the alternate load cell. The average discharge throughout the set of tests was 28,700 cfs. Figure 26 is a picture taken during testing with five bulkheads in place (blue) and the sixth bulkhead being lowered (yellow). The top of the lifting beam is at an elevation of 908.2 ft in the figure. Figure 27 displays the initial and final WSEs. These are presented separately as opposed to averaging the measurements throughout the testing so that the difference in headwater can be tracked as it relates to bulkheads in the water. Figure 28 through Figure 33 display the load data for each bulkhead placement up to six bulkheads in place. Error bars provide the maximum and minimum hydrodynamic force measured at each location.

Figure 26. The 50-year event all gates open.

Figure 27. The 50-year event initial (left) and final (right) WSEs (feet).

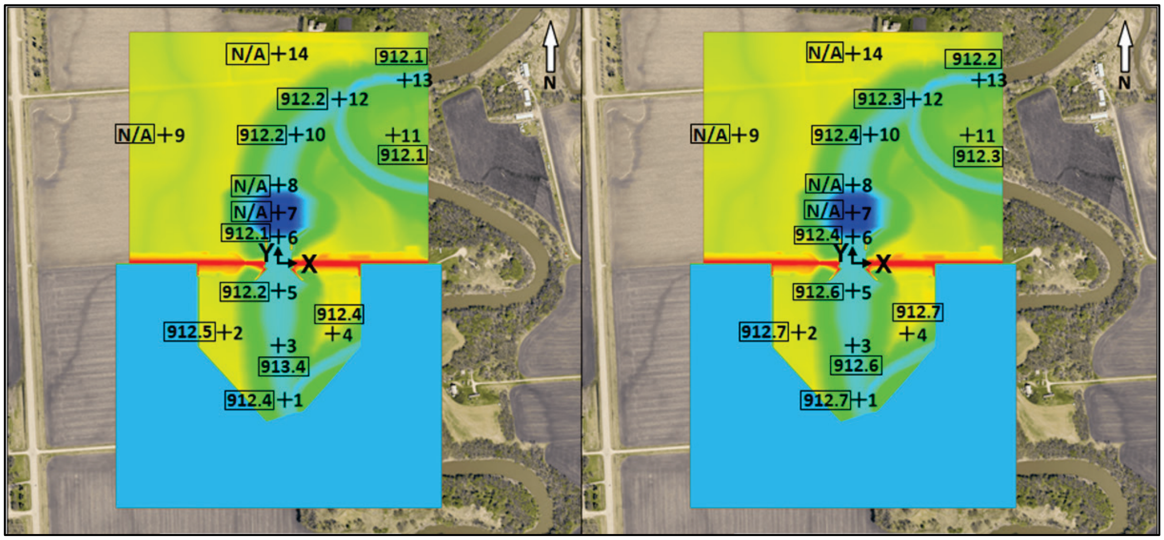


Figure 28. First bulkhead 50-year event vertical hydraulic forces.

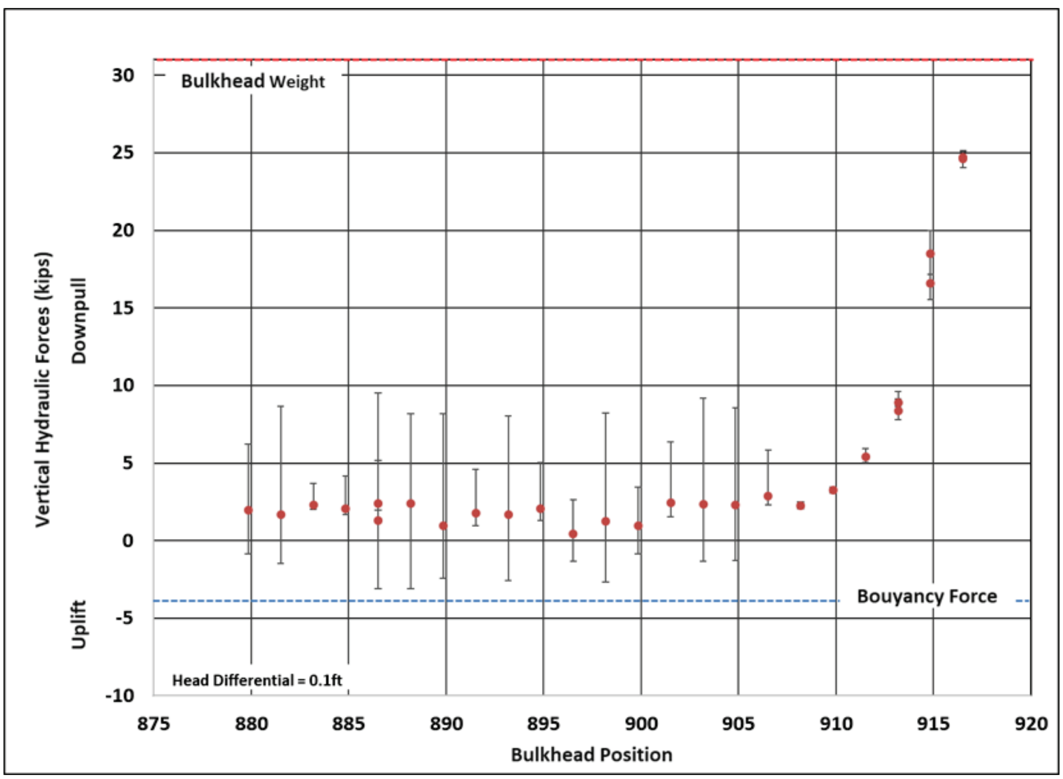


Figure 29. Second bulkhead 50-year event vertical hydraulic forces.

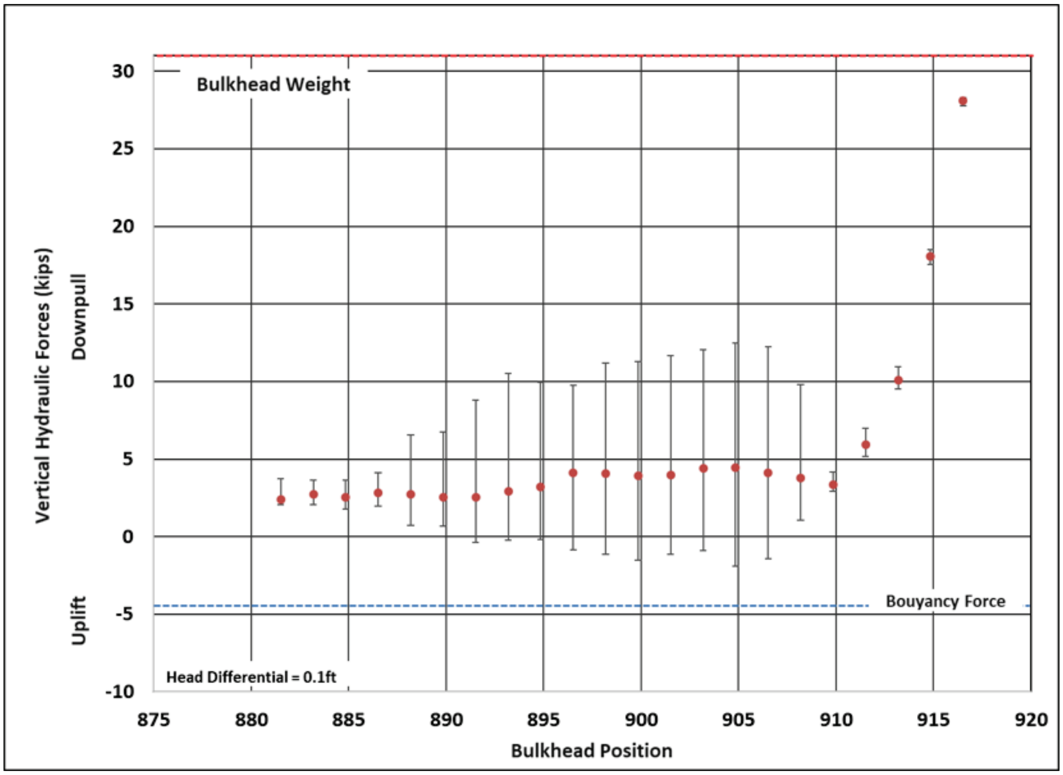


Figure 30. Third bulkhead 50-year event vertical hydraulic forces.

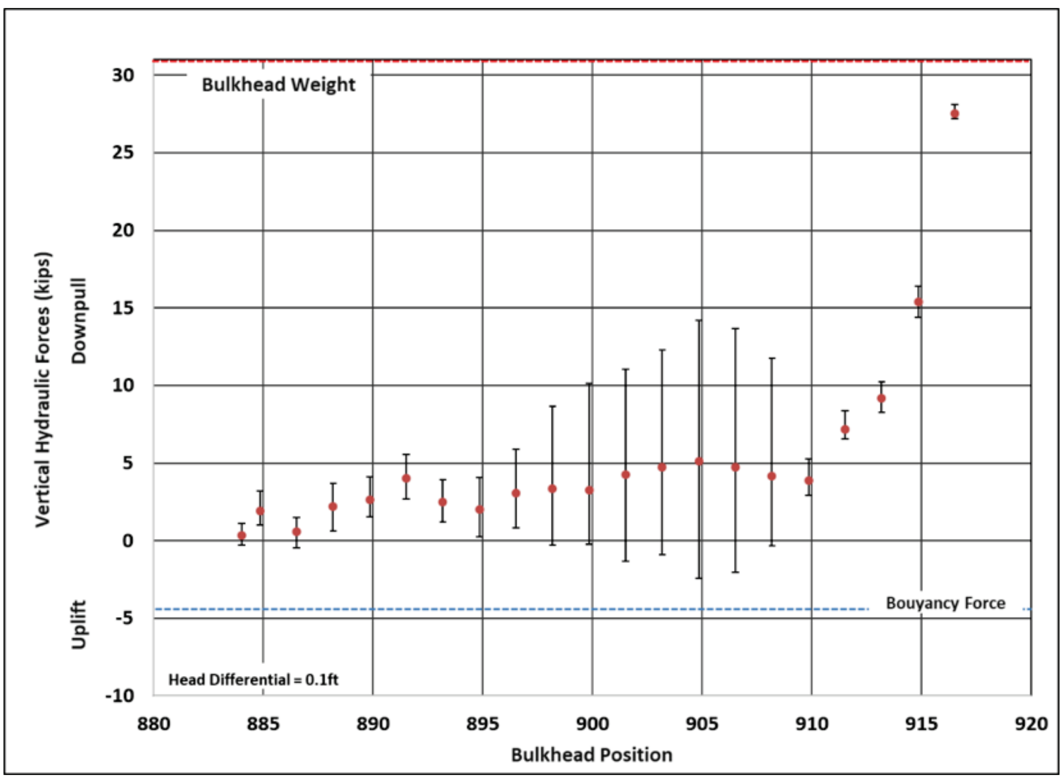


Figure 31. Fourth bulkhead 50-year event vertical hydraulic forces.

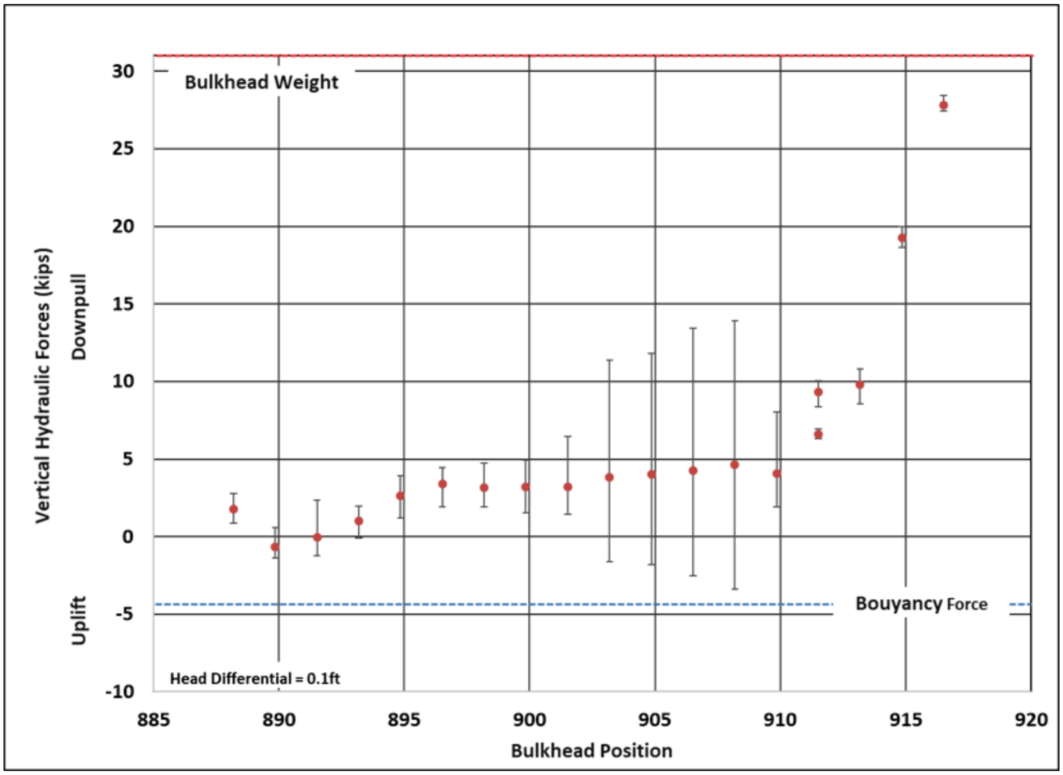


Figure 32. Fifth bulkhead 50-year event vertical hydraulic forces.

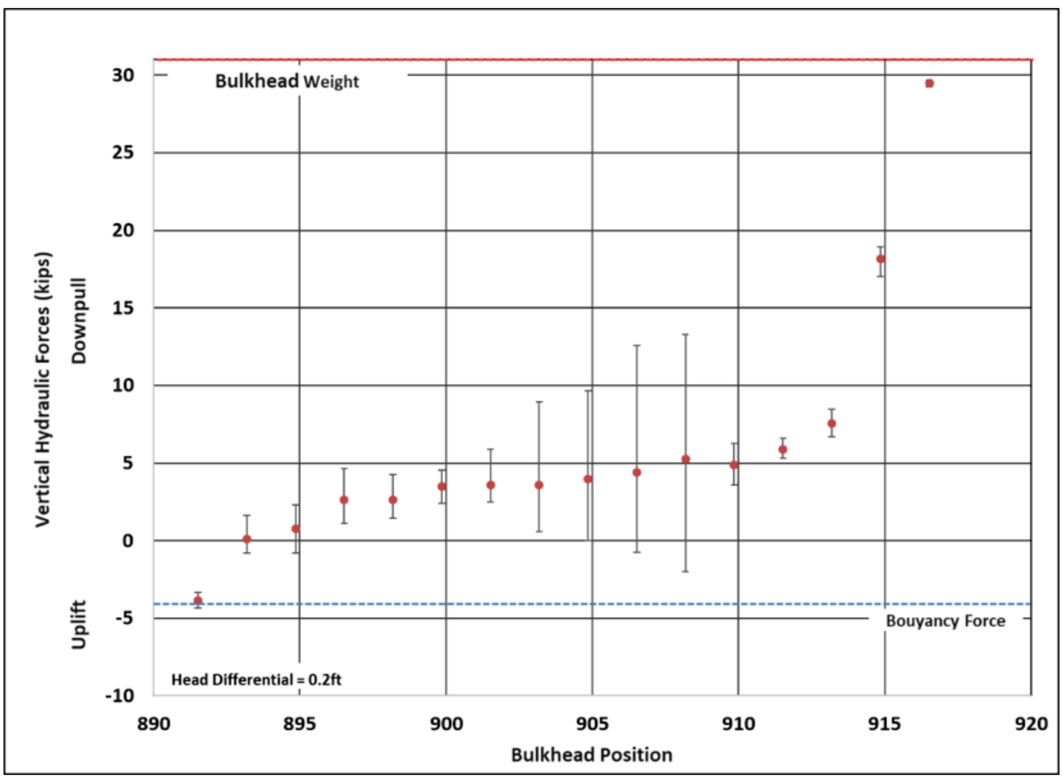
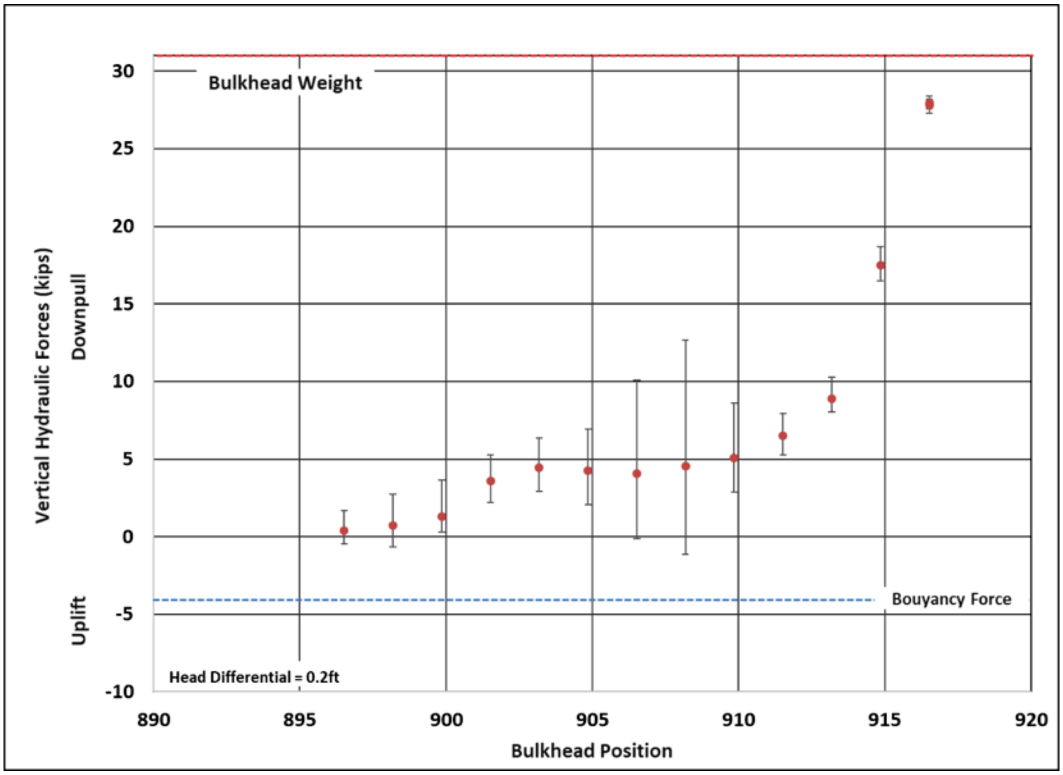


Figure 33. Sixth bulkhead 50-year event vertical hydraulic forces.



3.2.3 Probable Maximum Flood (PMF)

For the PMF test, load data were only collected with five bulkheads in position and lowering the sixth (Figure 34) with all three gates completely open. It was understood that this was most likely the worst-case scenario and thus was the only one tested. The final WSEs can be seen in Figure 35 with six total bulkheads in position. The flow was approximately 103,300 cfs. Note that there was water at gage 14; however, the gage was reporting erroneous data and thus is reported as N/A here. Also, the headwater elevation at gage 5 is well above the maximum allowable WSE of 923.5 ft. Figure 36 plots the load data for the PMF scenario. Error bars provide the maximum and minimum hydrodynamic force measured at each location. Testing was executed over three separate days denoted by 1, 2, and 3 in the figure. Note the incredibly high downpull forces acting on the bulkhead.

Figure 34. PMF test.

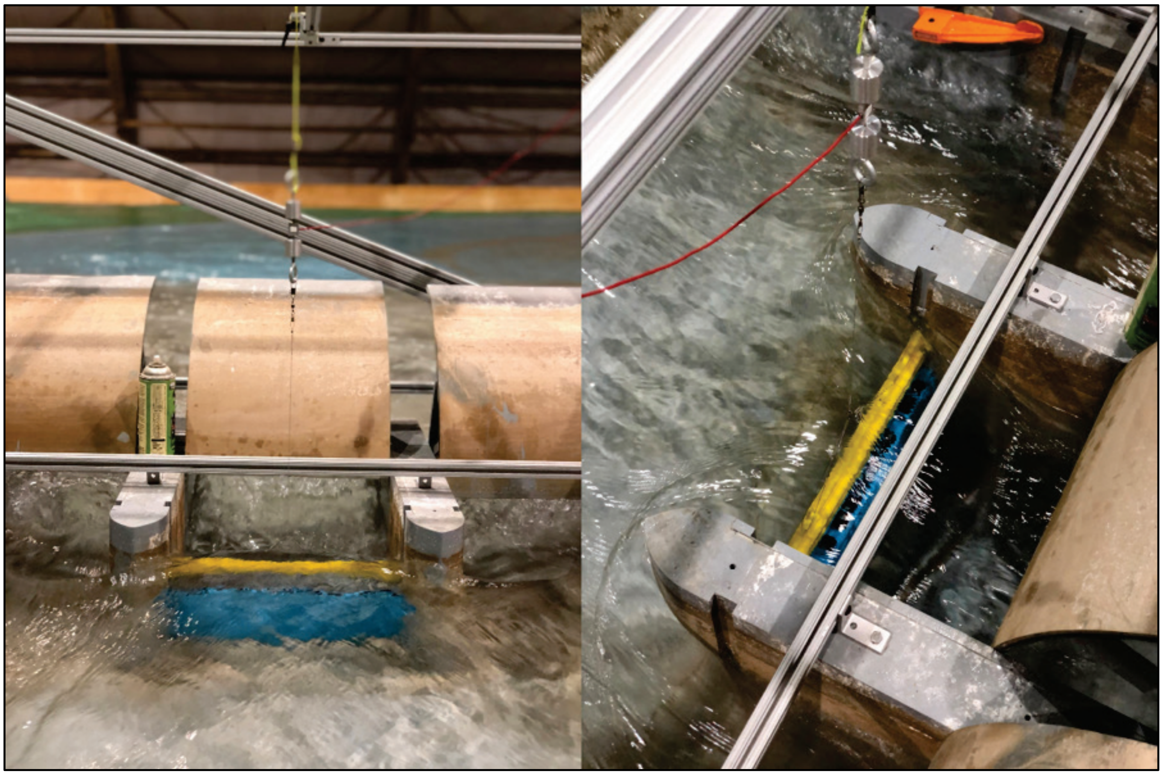


Figure 35. PMF final WSEs (feet).

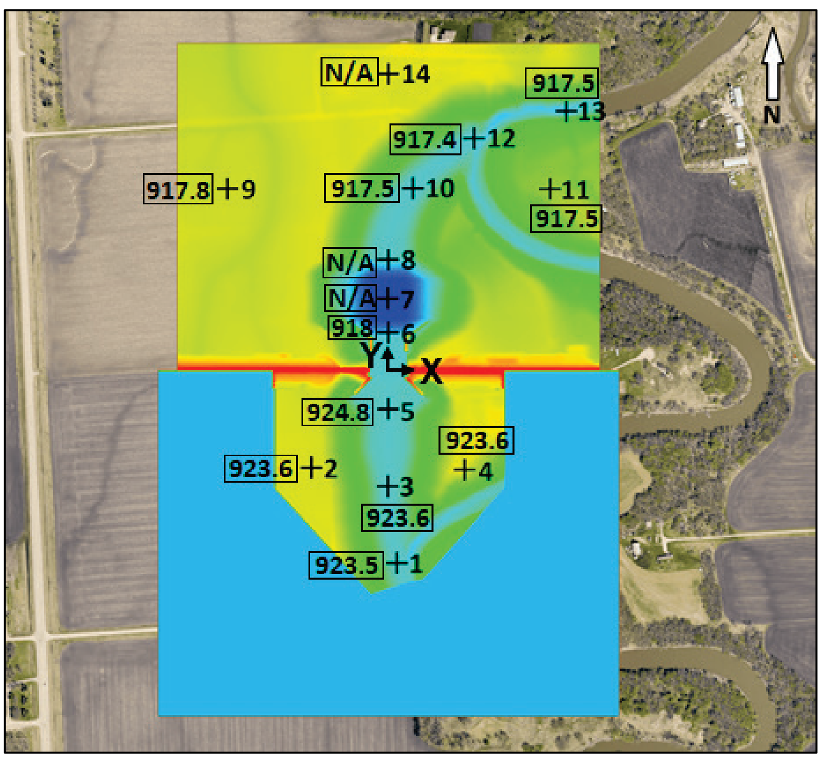
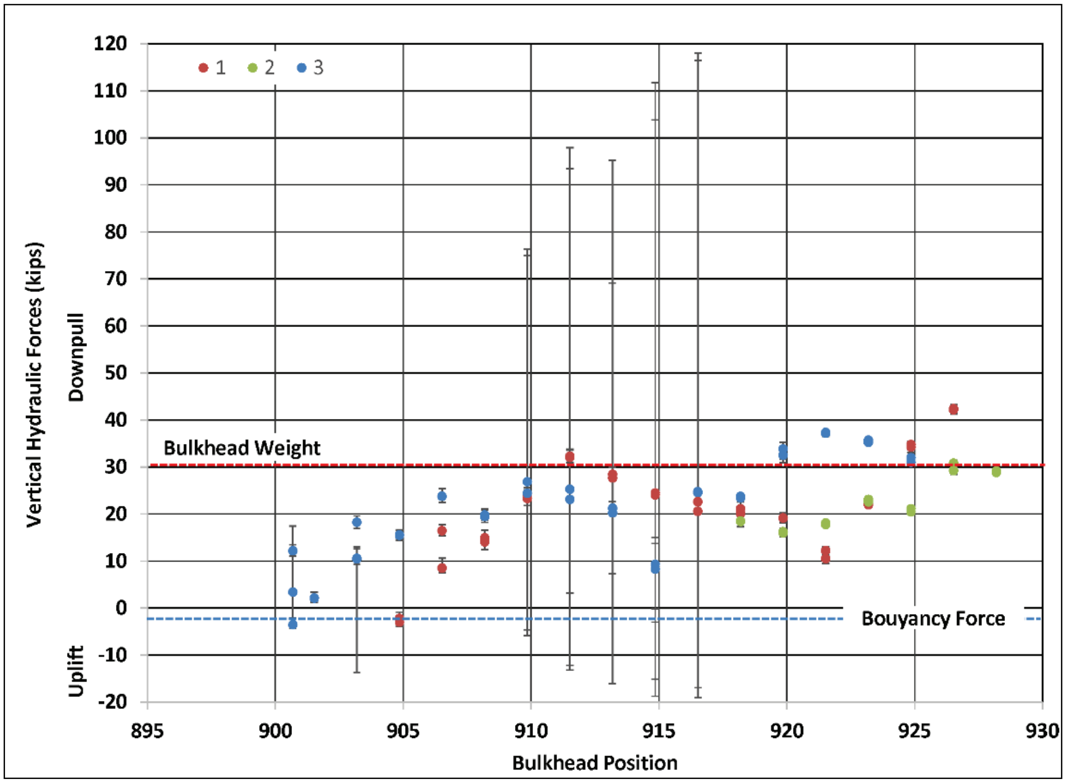


Figure 36. Sixth bulkhead PMF event vertical hydraulic forces.



3.2.4 20-year event (downstream bulkhead placement)

Up to this point, all tests were conducted by placing the bulkheads in the pier slots upstream of the radial tainter gates. For this test, the bulkheads were placed in the pier slots downstream of the tainter gates. The 20-year event was simulated (east and west gates closed). Figure 37 is a view looking upstream of this scenario with five bulkheads in place (blue) while lowering the sixth bulkhead (yellow). The top of the lifting beam is at an elevation of 902.5 ft. The initial/final WSE for this scenario can be seen in Figure 38 and had an average discharge of 12,300 cfs. Figure 39 – Figure 44 display the load data for the bulkhead placement from the first bulkhead to six bulkheads in place. Error bars provide the maximum and minimum hydrodynamic force measured at each location. Note that compared to the 20-year event east and west gates closed event with bulkheads placed in the upstream pier slots, there is more uplift force for the downstream pier slot placement. Also note that there are several positions in the water column that the bulkhead experiences heavy downpull forces in the 5 – 30 kip range.

Figure 37. The 20-year event (east and west gates closed) downstream pier slot bulkhead placement test (looking upstream).

Figure 38. The 20-year event (east and west gates closed) downstream pier slot bulkhead placement test WSEs (initial on the left; final on the right).

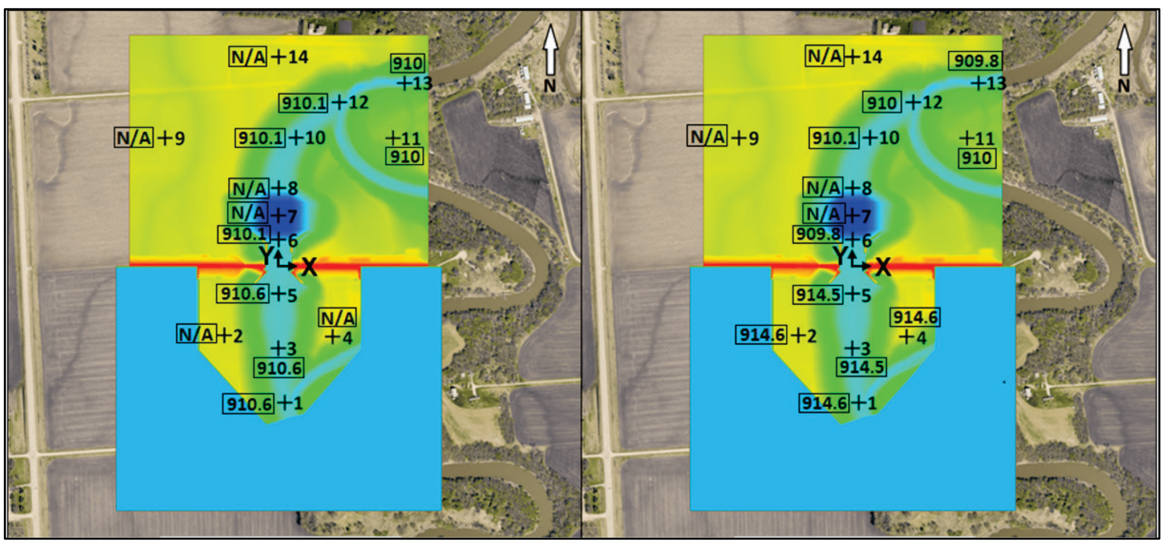


Figure 39. First bulkhead 20-year event (downstream pier slots) vertical hydraulic forces.

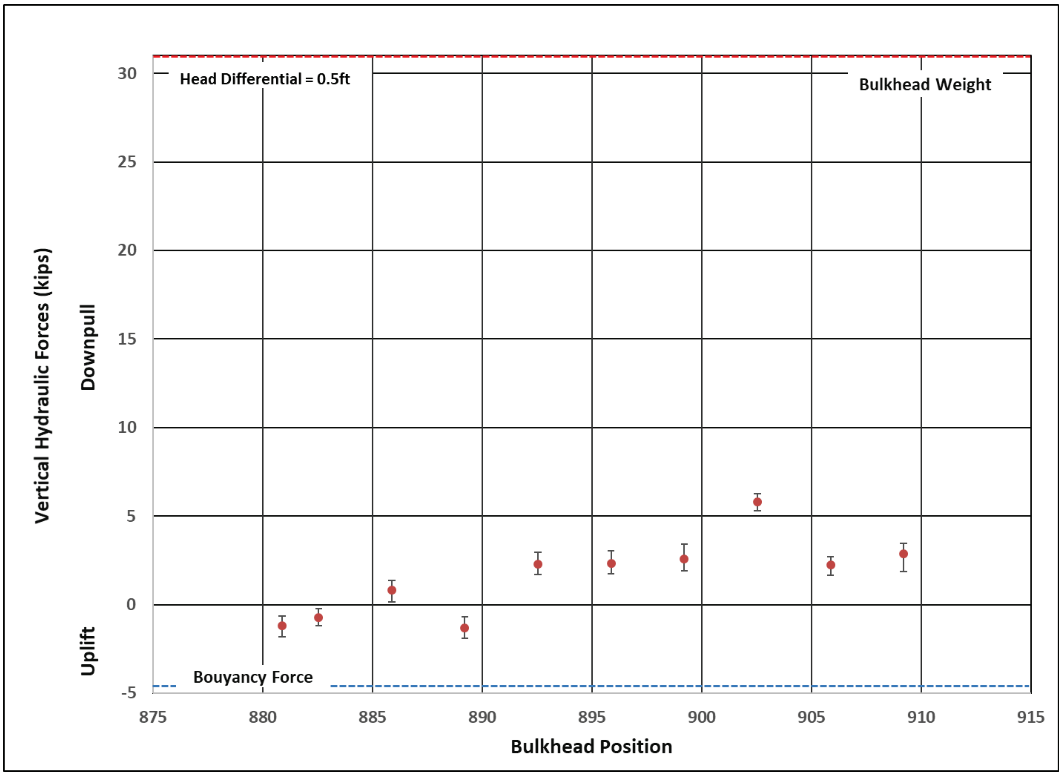


Figure 40. Second bulkhead 20-year event (downstream pier slots) vertical hydraulic forces.

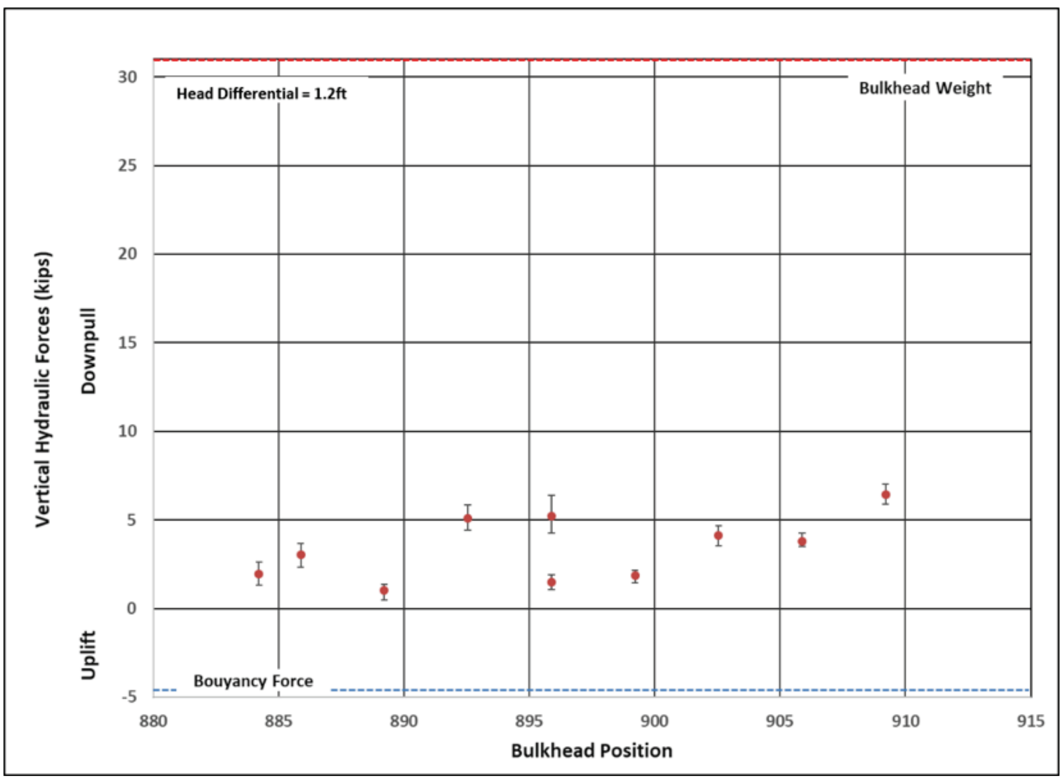


Figure 41. Third bulkhead 20-year event (downstream pier slots) vertical hydraulic forces.

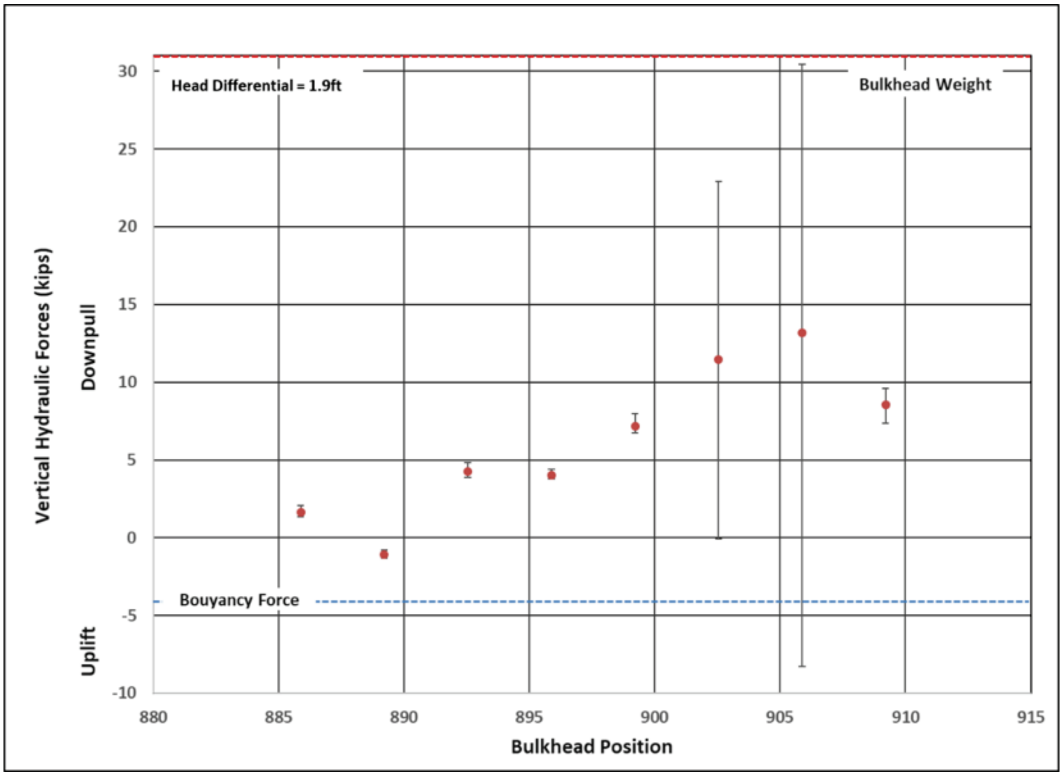


Figure 42. Fourth bulkhead 20-year event (downstream pier slots) vertical hydraulic forces.

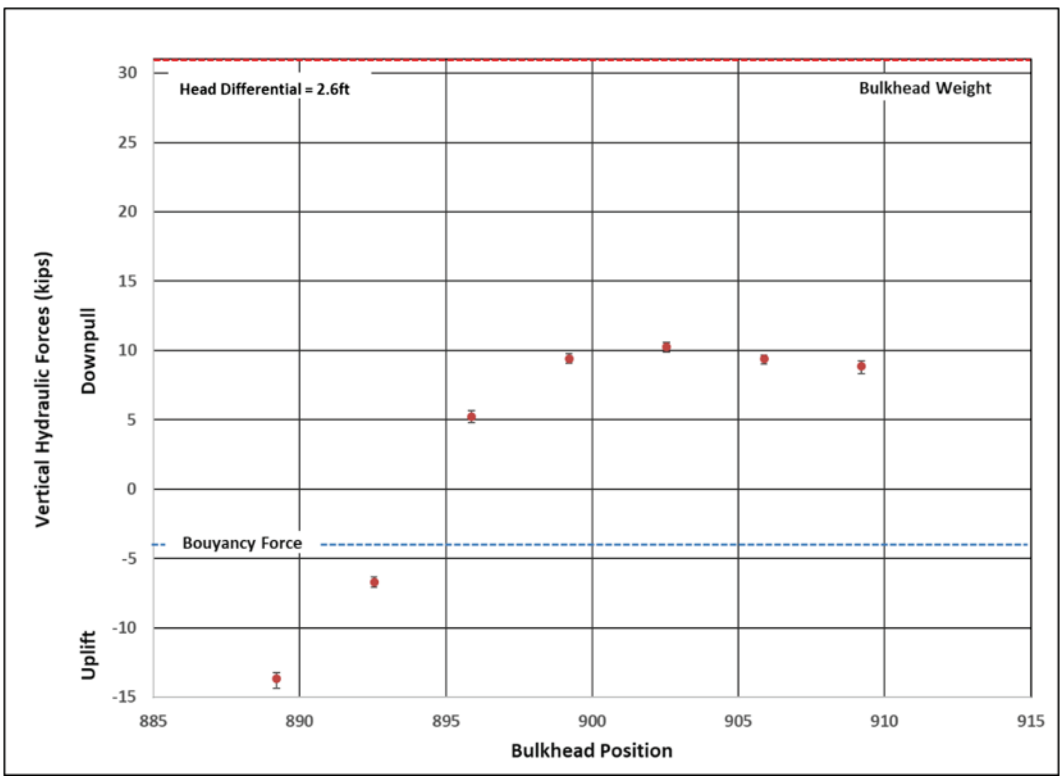


Figure 43. Fifth bulkhead 20-year event (downstream pier slots) vertical hydraulic forces.

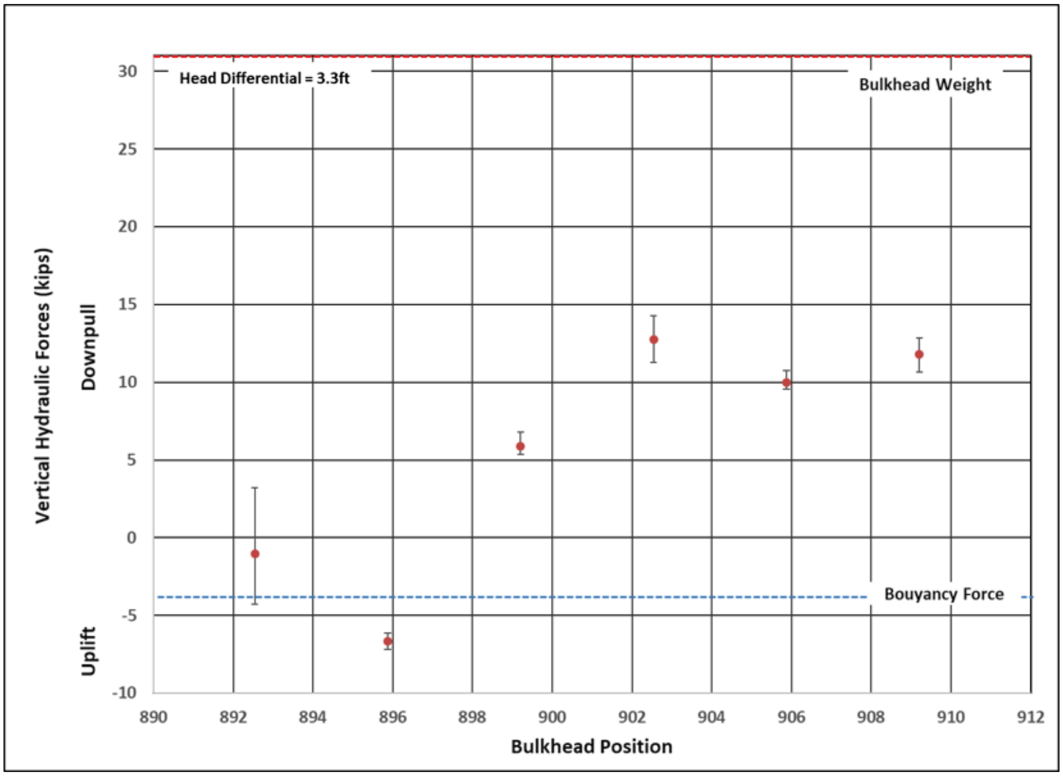
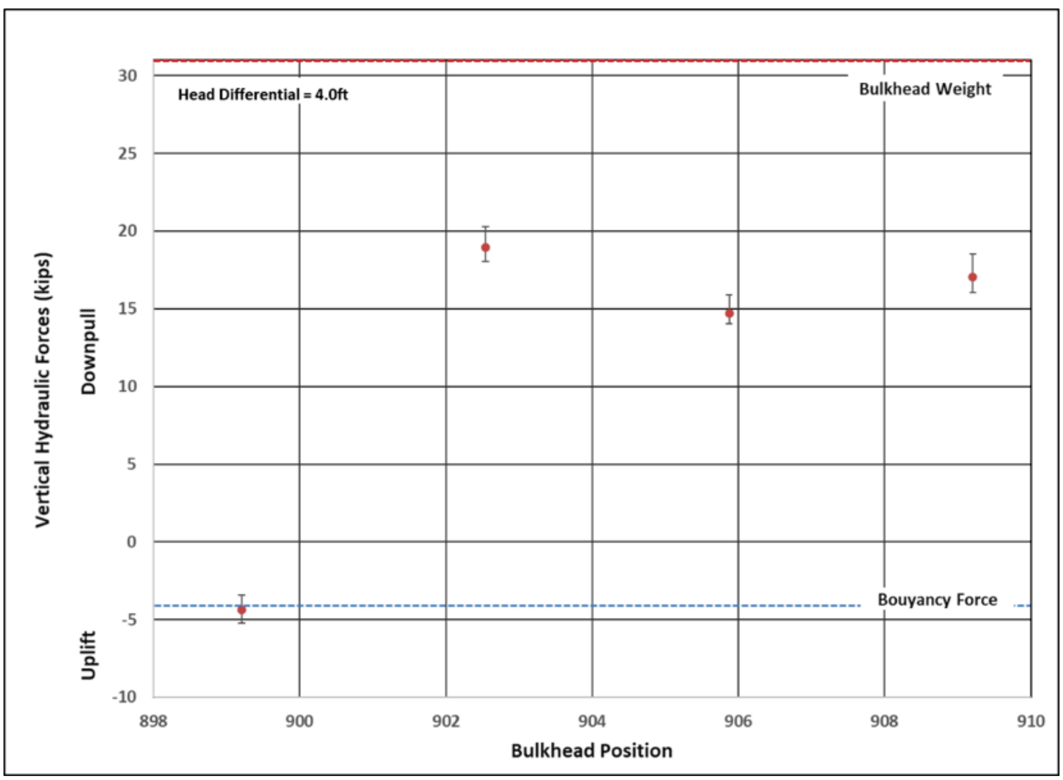


Figure 44. Sixth bulkhead 20-year event (downstream pier slots) vertical hydraulic forces.



4 Conclusions and Recommendations

For each of the test conditions, except for the 20-year event with all gates open, it was found that at some point the maximum allowable load of 40 kips was either met and/or exceeded. The 40-kip allowable load includes the buoyant weight of the bulkhead and lifting beam plus the vertical hydraulic load. Furthermore, for higher flow conditions, the bulkhead experienced vertical movement or *jumping* during static load data collection at certain points in the water column for certain boundary conditions. This is very problematic and turns dead load into dynamic load or live load. This instability is not desired and could create bulkhead binding issues and possibly overload the crane.

The occurrence of differential head across the structure appears to be one of the variables that contributes to the high load values being exerted on the bulkhead as suggested by Hite and Pickering (1983). Also, the unpredictable resulting load data as the nappe overtops the bulkhead and the lifting beam confirm previous studies. Part of this is related to the proposed bulkhead's geometry (i.e., flat bottom versus 45 deg angled bottom). This has impacts on how flow separates beyond the bulkhead and potential pressure changes underneath the bulkhead.

It is recommended that the current bulkhead design and operation plan are not to be deployed in flow events that exceed the 20-year event condition with all gates open. The tests with the east and west gates closed indicate that large load fluctuations occurred, and this would also be expected with lower flow events if these gates are closed. Since further testing was not conducted on lower flows than the 20-year event, it cannot be stated what that threshold flow/boundary condition set is.

References

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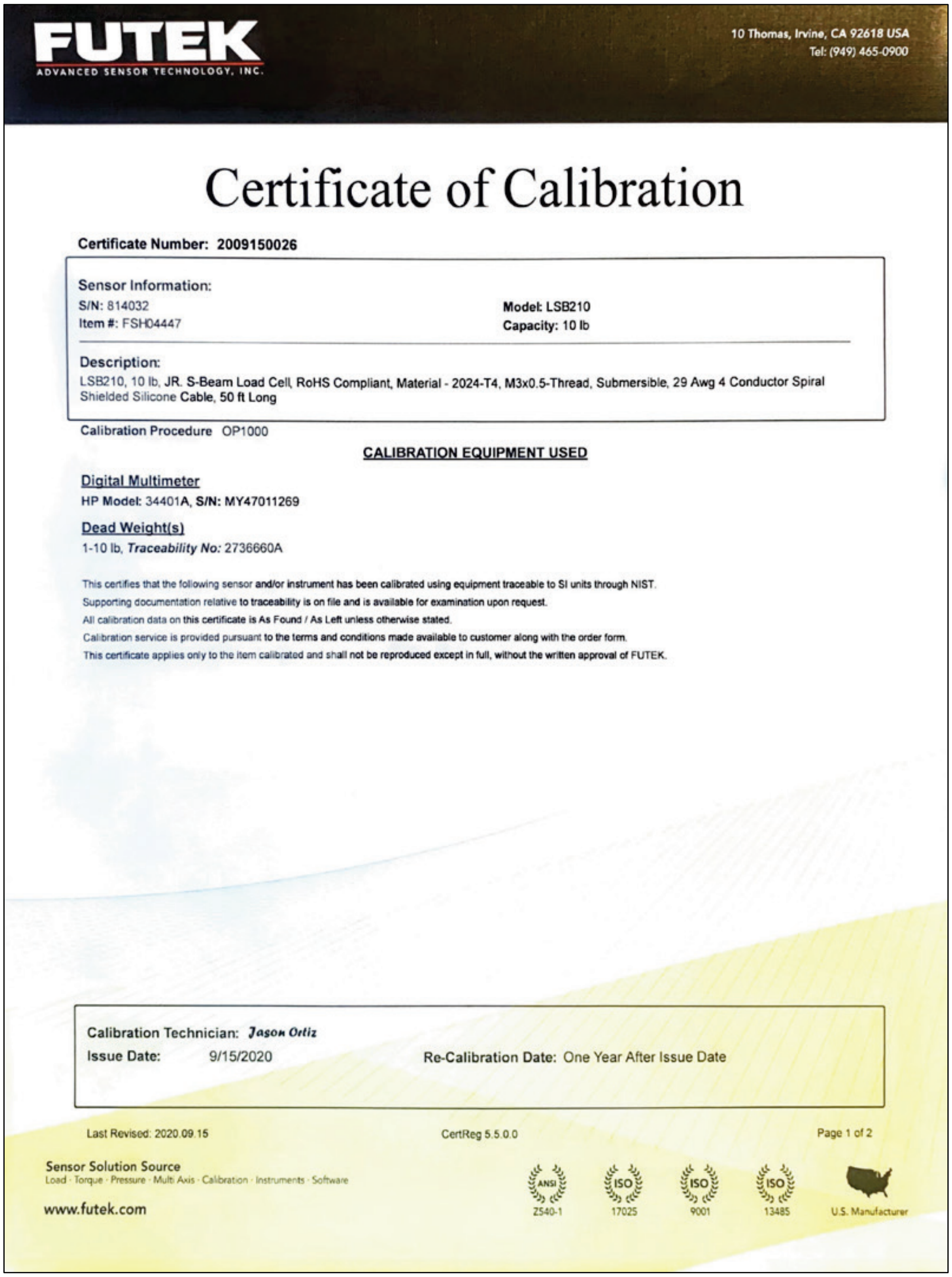
Appendix A: Load Cell Calibrations

Figure 45 – Figure 52 present the specific FUTEK calibration data for each of the load cells (Alternate FUTEK load cell was only used for the 50-year event).

Figure 45. FUTEK load cell certificate of calibration.



FUTEK
ADVANCED SENSOR TECHNOLOGY, INC.

10 Thomas, Irvine, CA 92618 USA
Tel: (949) 465-0900

Certificate of Calibration

Certificate Number: 2009150026

Sensor Information:
S/N: 814032
Item #: FSH04447
Model: LSB210
Capacity: 10 lb

Description:
LSB210, 10 lb, JR. S-Beam Load Cell, RoHS Compliant, Material - 2024-T4, M3x0.5-Thread, Submersible, 29 Awg 4 Conductor Spiral Shielded Silicone Cable, 50 ft Long

Calibration Procedure OP1000

CALIBRATION EQUIPMENT USED

Digital Multimeter
HP Model: 34401A, S/N: MY47011269

Dead Weight(s)
1-10 lb, *Traceability No:* 2736660A

This certifies that the following sensor and/or instrument has been calibrated using equipment traceable to SI units through NIST.
Supporting documentation relative to traceability is on file and is available for examination upon request.
All calibration data on this certificate is As Found / As Left unless otherwise stated.
Calibration service is provided pursuant to the terms and conditions made available to customer along with the order form.
This certificate applies only to the item calibrated and shall not be reproduced except in full, without the written approval of FUTEK.

Calibration Technician: *Jason Ortiz*
Issue Date: 9/15/2020
Re-Calibration Date: One Year After Issue Date

Last Revised: 2020.09.15
CertReg 5.5.0.0
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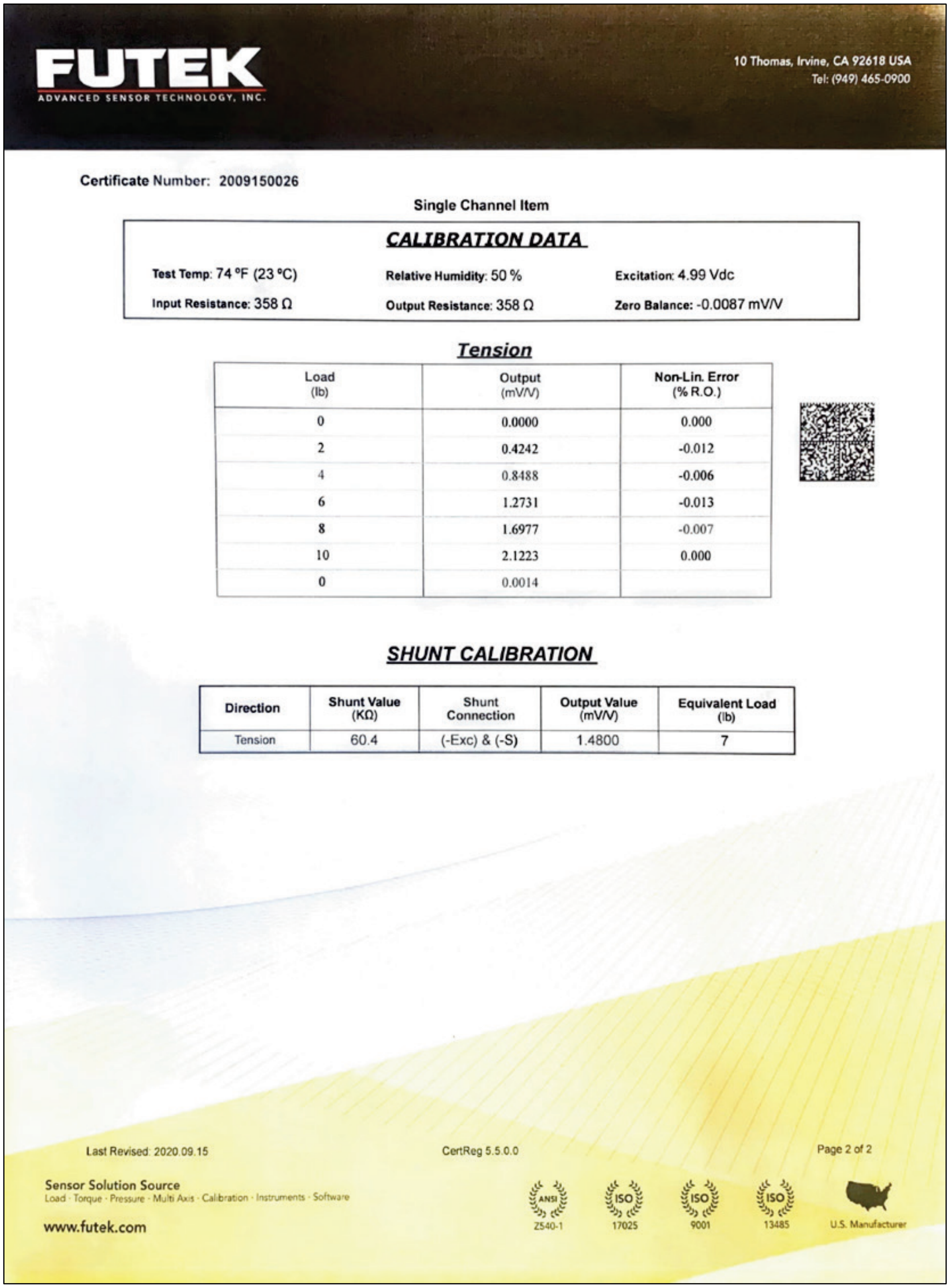
ANSI Z540-1 ISO 17025 ISO 9001 ISO 13485 U.S. Manufacturer

Figure 46. FUTEK load cell calibration data.



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10 Thomas, Irvine, CA 92618 USA
Tel: (949) 465-0900

Certificate Number: 2009150026

Single Channel Item

CALIBRATION DATA

Test Temp: 74 °F (23 °C)	Relative Humidity: 50 %	Excitation: 4.99 Vdc
Input Resistance: 358 Ω	Output Resistance: 358 Ω	Zero Balance: -0.0087 mV/V

Tension

Load (lb)	Output (mV/V)	Non-Lin. Error (% R.O.)
0	0.0000	0.000
2	0.4242	-0.012
4	0.8488	-0.006
6	1.2731	-0.013
8	1.6977	-0.007
10	2.1223	0.000
0	0.0014	

SHUNT CALIBRATION

Direction	Shunt Value (KΩ)	Shunt Connection	Output Value (mV/V)	Equivalent Load (lb)
Tension	60.4	(-Exc) & (-S)	1.4800	7

Last Revised: 2020.09.15 CertReg 5.5.0.0 Page 2 of 2

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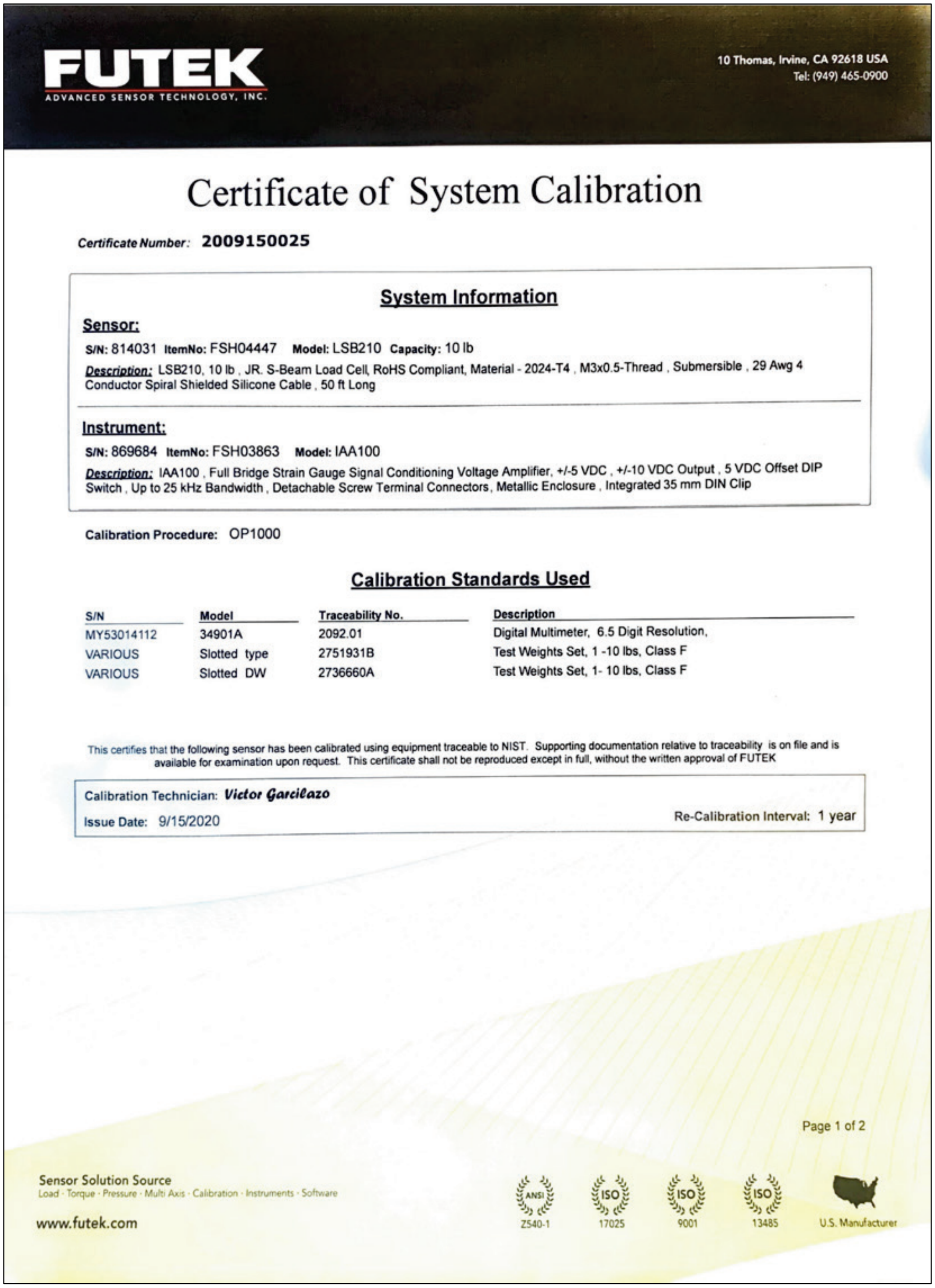
ANSI Z540-1 ISO 17025 ISO 9001 ISO 13485 U.S. Manufacturer

Figure 47. FUTEK load cell certificate of system calibration.



FUTEK
ADVANCED SENSOR TECHNOLOGY, INC.

10 Thomas, Irvine, CA 92618 USA
Tel: (949) 465-0900

Certificate of System Calibration

Certificate Number: **2009150025**

System Information

Sensor:

S/N: 814031 **ItemNo:** FSH04447 **Model:** LSB210 **Capacity:** 10 lb

Description: LSB210, 10 lb , JR. S-Beam Load Cell, RoHS Compliant, Material - 2024-T4 , M3x0.5-Thread , Submersible , 29 Awg 4 Conductor Spiral Shielded Silicone Cable , 50 ft Long

Instrument:

S/N: 869684 **ItemNo:** FSH03863 **Model:** IAA100

Description: IAA100 , Full Bridge Strain Gauge Signal Conditioning Voltage Amplifier, +/-5 VDC , +/-10 VDC Output , 5 VDC Offset DIP Switch , Up to 25 kHz Bandwidth , Detachable Screw Terminal Connectors, Metallic Enclosure , Integrated 35 mm DIN Clip

Calibration Procedure: OP1000

Calibration Standards Used

S/N	Model	Traceability No.	Description
MY53014112	34901A	2092.01	Digital Multimeter, 6.5 Digit Resolution,
VARIOUS	Slotted type	2751931B	Test Weights Set, 1 -10 lbs, Class F
VARIOUS	Slotted DW	2736660A	Test Weights Set, 1- 10 lbs, Class F

This certifies that the following sensor has been calibrated using equipment traceable to NIST. Supporting documentation relative to traceability is on file and is available for examination upon request. This certificate shall not be reproduced except in full, without the written approval of FUTEK

Calibration Technician: *Victor Garcilazo*

Issue Date: 9/15/2020 Re-Calibration Interval: 1 year

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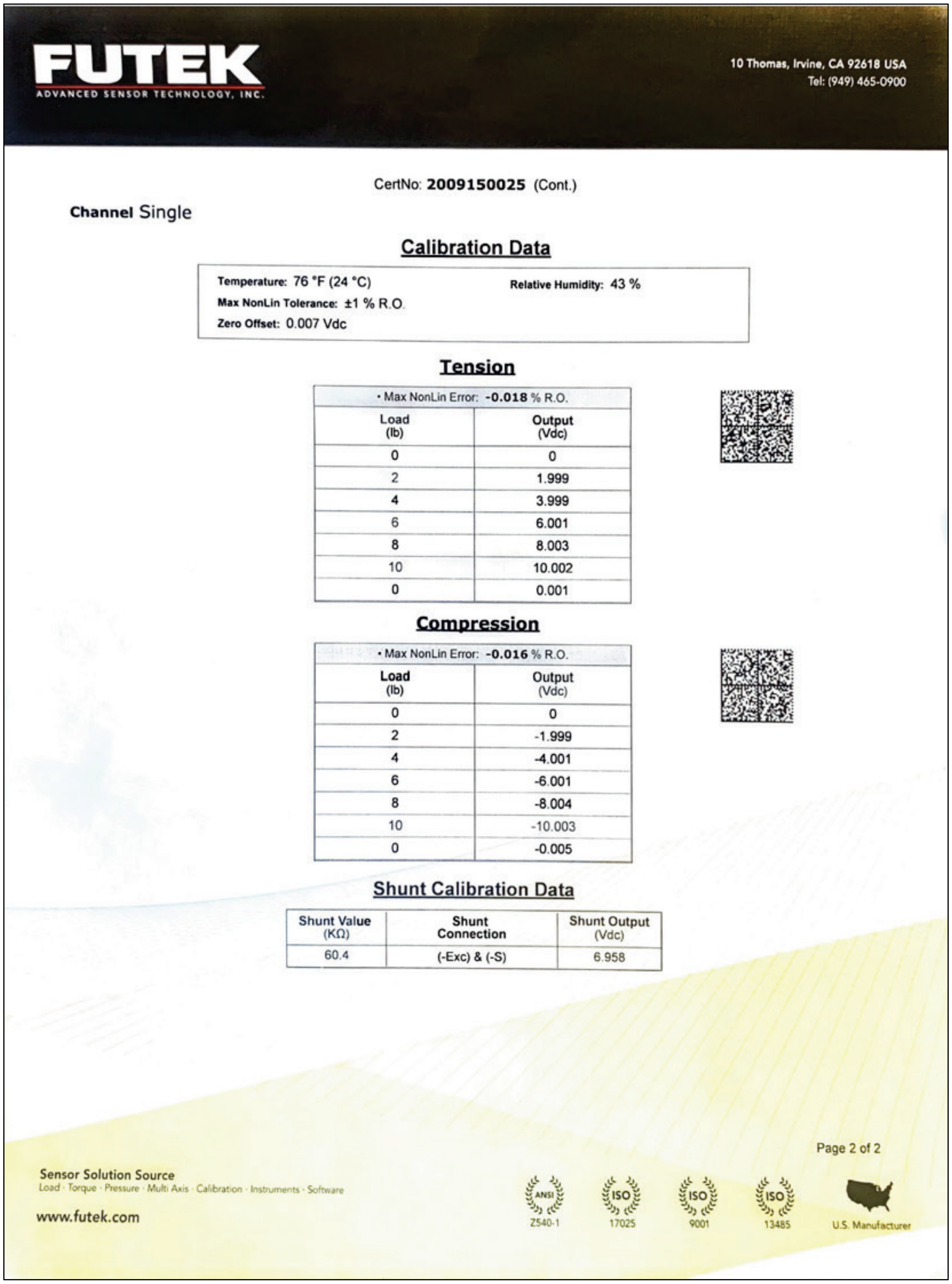
ANSI Z540-1 ISO 17025 ISO 9001 ISO 13485 U.S. Manufacturer

Figure 48. FUTEK load cell system calibration.



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ADVANCED SENSOR TECHNOLOGY, INC.

10 Thomas, Irvine, CA 92618 USA
Tel: (949) 465-0900

CertNo: **2009150025** (Cont.)

Channel Single

Calibration Data

Temperature: 76 °F (24 °C) **Relative Humidity:** 43 %
Max NonLin Tolerance: ±1 % R.O.
Zero Offset: 0.007 Vdc

Tension

• Max NonLin Error: **-0.018** % R.O.

Load (lb)	Output (Vdc)
0	0
2	1.999
4	3.999
6	6.001
8	8.003
10	10.002
0	0.001

Compression

• Max NonLin Error: **-0.016** % R.O.

Load (lb)	Output (Vdc)
0	0
2	-1.999
4	-4.001
6	-6.001
8	-8.004
10	-10.003
0	-0.005

Shunt Calibration Data

Shunt Value (KΩ)	Shunt Connection	Shunt Output (Vdc)
60.4	(-Exc) & (-S)	6.958

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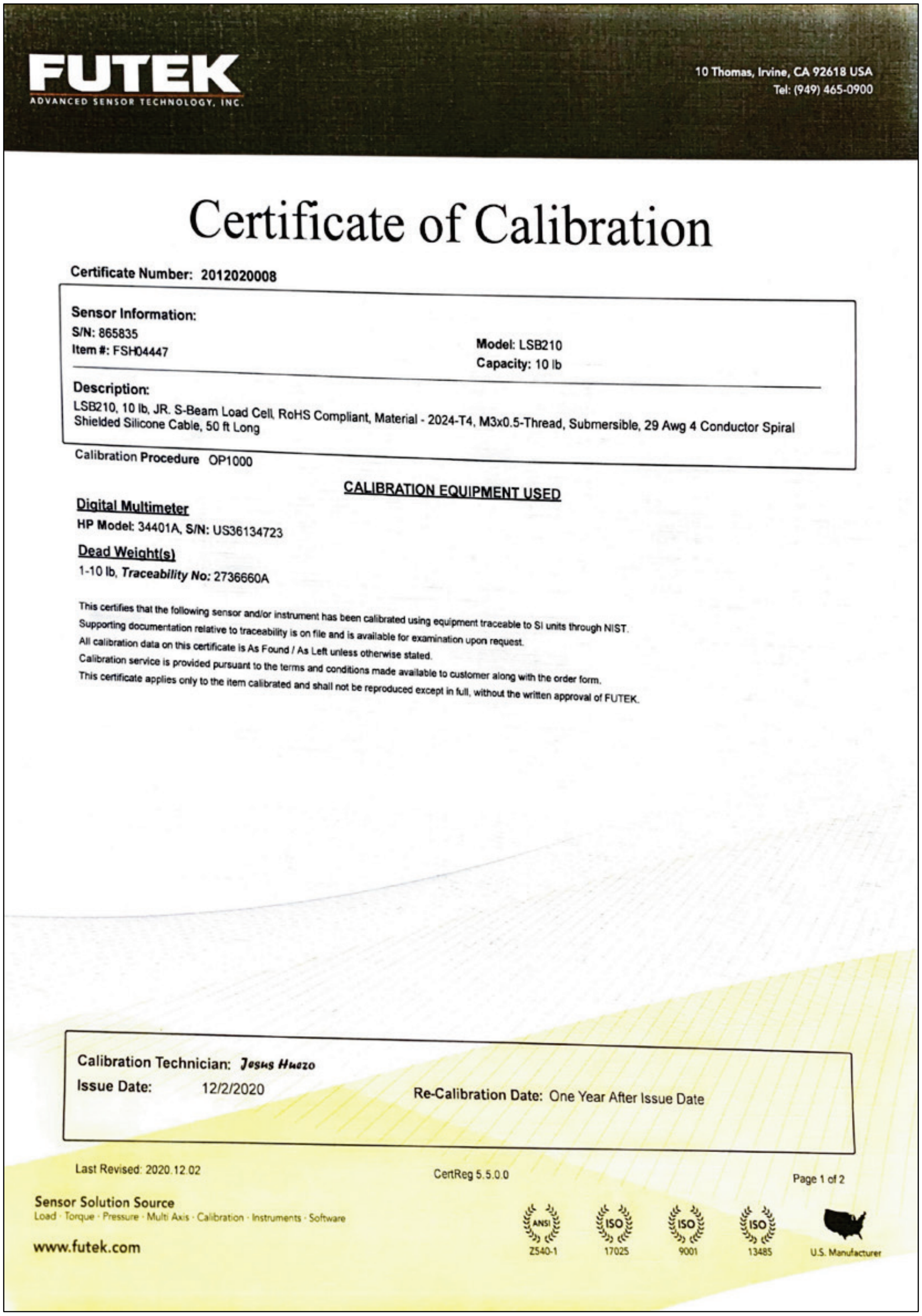
The load cell used for most of the tests happened to come off one of the last tests and suffered damage. The replacement load cell calibration can be seen in Figure 49 – Figure 52.

Figure 49. Alternate FUTEK load cell certificate of calibration.



FUTEK
ADVANCED SENSOR TECHNOLOGY, INC.

10 Thomas, Irvine, CA 92618 USA
Tel: (949) 465-0900

Certificate of Calibration

Certificate Number: 2012020008

Sensor Information:
S/N: 865835
Item #: FSH04447
Model: LSB210
Capacity: 10 lb

Description:
LSB210, 10 lb, JR. S-Beam Load Cell, RoHS Compliant, Material - 2024-T4, M3x0.5-Thread, Submersible, 29 Awg 4 Conductor Spiral Shielded Silicone Cable, 50 ft Long

Calibration **Procedure** OP1000

CALIBRATION EQUIPMENT USED

Digital Multimeter
HP Model: 34401A, **S/N:** US36134723

Dead Weight(s)
1-10 lb, ***Traceability No:*** 2736660A

This certifies that the following sensor and/or instrument has been calibrated using equipment traceable to SI units through NIST.
Supporting documentation relative to traceability is on file and is available for examination upon request.
All calibration data on this certificate is As Found / As Left unless otherwise stated.
Calibration service is provided pursuant to the terms and conditions made available to customer along with the order form.
This certificate applies only to the item calibrated and shall not be reproduced except in full, without the written approval of FUTEK.

Calibration Technician: *Jesus Huezo*
Issue Date: 12/2/2020
Re-Calibration Date: One Year After Issue Date

Last Revised: 2020.12.02
CertReg 5.5.0.0
Page 1 of 2

Sensor Solution Source
Load · Torque · Pressure · Multi Axis · Calibration · Instruments · Software
www.futek.com

ANSI Z540-1 · ISO 17025 · ISO 9001 · ISO 13485 · U.S. Manufacturer

Figure 50. Alternate FUTEK load cell calibration.

FUTEK
ADVANCED SENSOR TECHNOLOGY, INC.

10 Thomas, Irvine, CA 92618 USA
Tel: (949) 465-0900

Certificate Number: 2012020008

Single Channel Item

CALIBRATION DATA

Test Temp: 76 °F (24 °C)	**Relative Humidity:** 42 %	**Excitation:** 5.01 Vdc
Input Resistance: 359 Ω	**Output Resistance:** 359 Ω	**Zero Balance:** 0.0095 mV/V

Tension

Load (lb)	Output (mV/V)	Non-Lin. Error (% R.O.)
0	-0.0003	0.000
2	0.4288	-0.015
4	0.8587	0.007
6	1.2880	0.002
8	1.7177	0.015
10	2.1468	0.000
0	0.0015	0.000

SHUNT CALIBRATION

Direction	Shunt Value (KΩ)	Shunt Connection	Output Value (mV/V)	Equivalent Load (lb)
Tension	60.4	(-Exc) & (-S)	1.5175	7

Last Revised: 2020.12.02 CertReg 5.5.0.0 Page 2 of 2

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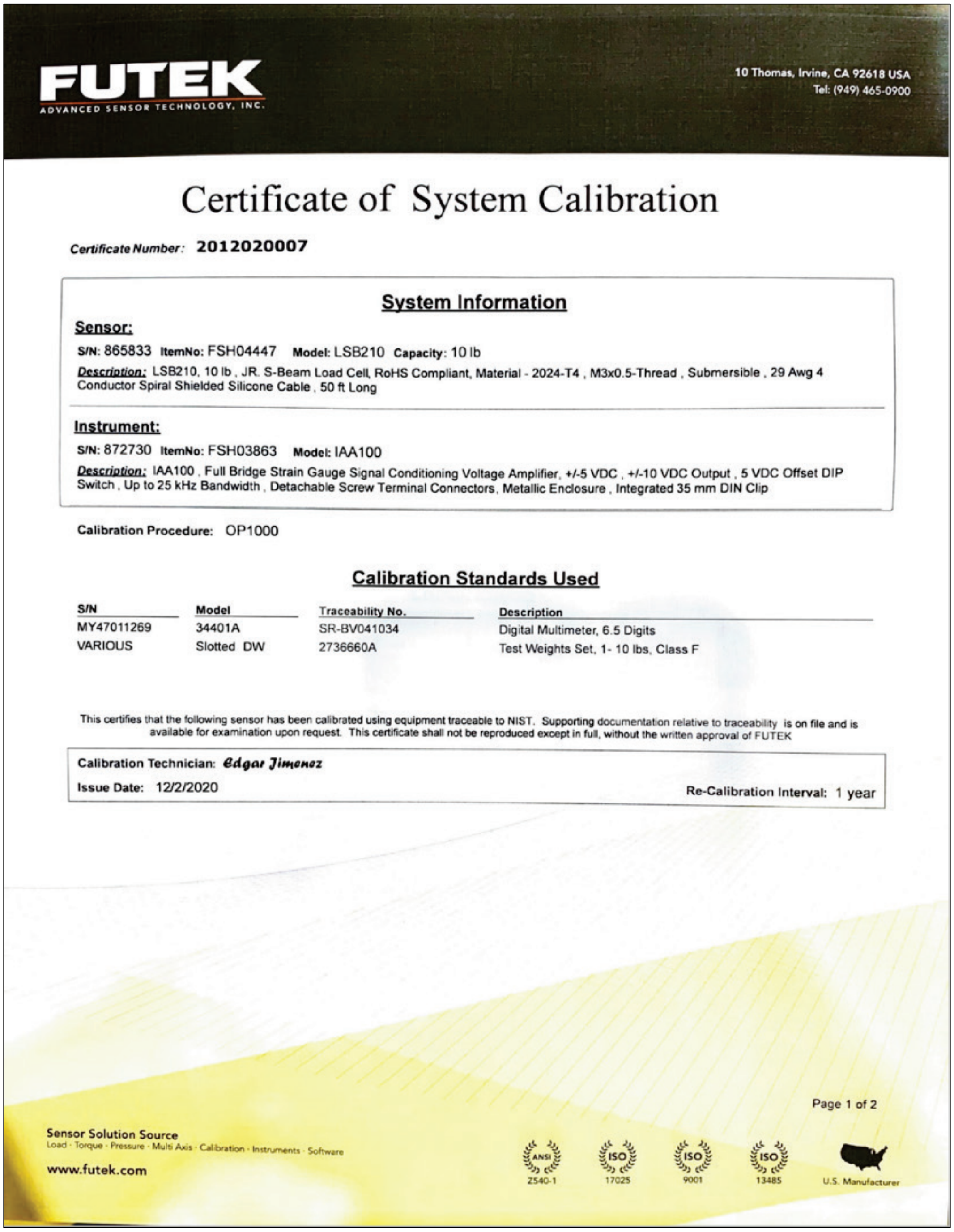
ANSI Z540-1 ISO 17025 ISO 9001 ISO 13485 U.S. Manufacturer

Figure 51. Alternate FUTEK load cell certificate of system calibration.



FUTEK
ADVANCED SENSOR TECHNOLOGY, INC.

10 Thomas, Irvine, CA 92618 USA
Tel: (949) 465-0900

Certificate of System Calibration

Certificate Number: **2012020007**

System Information

Sensor:

S/N: 865833 **ItemNo:** FSH04447 **Model:** LSB210 **Capacity:** 10 lb

Description: LSB210, 10 lb , JR. S-Beam Load Cell, RoHS Compliant, Material - 2024-T4 , M3x0.5-Thread , Submersible , 29 Awg 4 Conductor Spiral Shielded Silicone Cable , 50 ft Long

Instrument:

S/N: 872730 **ItemNo:** FSH03863 **Model:** IAA100

Description: IAA100 , Full Bridge Strain Gauge Signal Conditioning Voltage Amplifier, +/-5 VDC , +/-10 VDC Output , 5 VDC Offset DIP Switch , Up to 25 kHz Bandwidth , Detachable Screw Terminal Connectors, Metallic Enclosure , Integrated 35 mm DIN Clip

Calibration Procedure: OP1000

Calibration Standards Used

S/N	Model	Traceability No.	Description
MY47011269	34401A	SR-BV041034	Digital Multimeter, 6.5 Digits
VARIOUS	Slotted DW	2736660A	Test Weights Set, 1- 10 lbs, Class F

This certifies that the following sensor has been calibrated using equipment traceable to NIST. Supporting documentation relative to traceability is on file and is available for examination upon request. This certificate shall not be reproduced except in full, without the written approval of FUTEK

Calibration Technician: *Edgar Jimenez*

Issue Date: 12/2/2020 **Re-Calibration Interval:** 1 year

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Sensor Solution Source
Load · Torque · Pressure · Multi Axis · Calibration · Instruments · Software
www.futek.com

ANSI Z540-1 ISO 17025 ISO 9001 ISO 13485 U.S. Manufacturer

Figure 52. Alternate FUTEK load cell system calibration.

FUTEK
ADVANCED SENSOR TECHNOLOGY, INC.
10 Thomas, Irvine, CA 92618 USA
Tel: (949) 465-0900

CertNo: **2012020007** (Cont.)

Channel Single

Calibration Data

Temperature: 71 °F (22 °C)	**Relative Humidity:** 31 %
Max NonLin Tolerance: ±1 % R.O.	
Zero Offset: -0.021 Vdc	

Tension

• Max NonLin Error: **-0.052** % R.O.

Load (lb)	Output (Vdc)
0	0
2	1.998
4	4.002
6	6.005
8	8.011
10	10.016
0	0.000

Compression

• Max NonLin Error: **-0.024** % R.O.

Load (lb)	Output (Vdc)
0	0
2	-2.002
4	-4.006
6	-6.011
8	-8.017
10	-10.021
0	-0.005

Shunt Calibration Data

Shunt Value (KΩ)	Shunt Connection	Shunt Output (Vdc)
60.4	(-Exc) & (-S)	6.881

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Appendix B: 20-year Event Test Results

Figure 53 – Figure 61 present the plots for the fourth – sixth bulkhead placement loadings.

Figure 53. Fourth bulkhead 20-year event (east and west gates closed) vertical hydraulic forces.

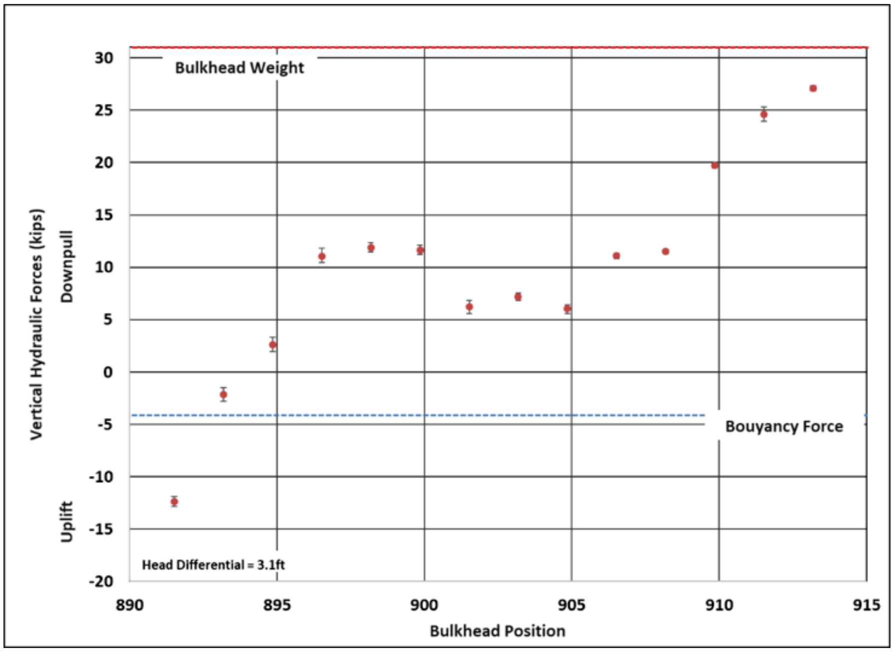


Figure 54. Fifth bulkhead 20-year event (east and west gates closed) vertical hydraulic forces.

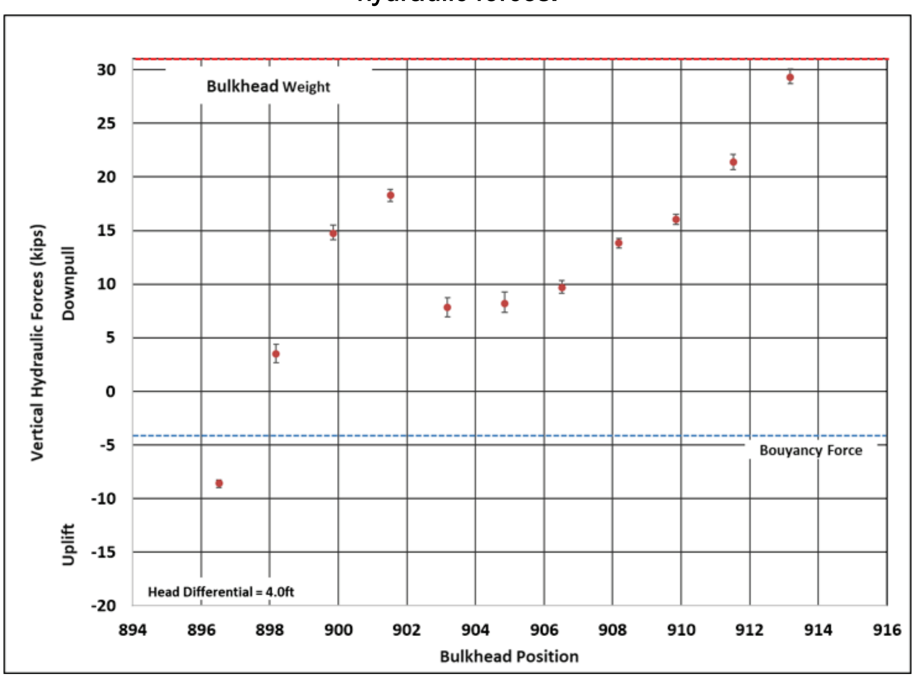


Figure 55. Sixth bulkhead 20-year event (east and west gates closed) vertical hydraulic forces.

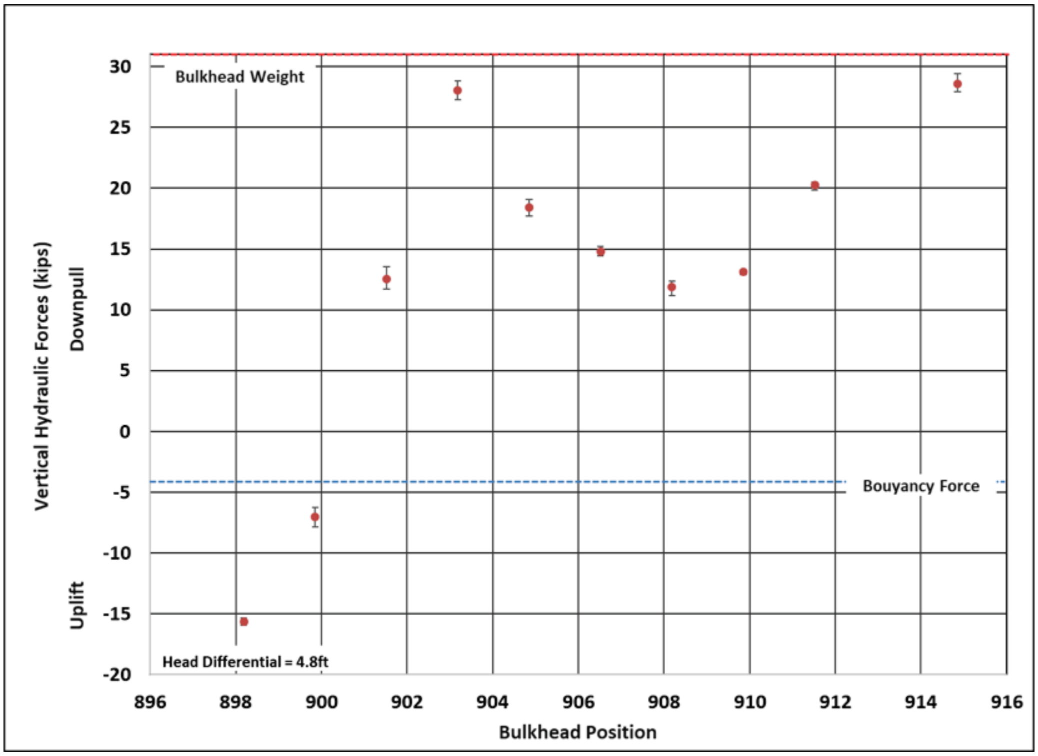


Figure 56. First bulkhead 20-year event (all gates open) vertical hydraulic forces.

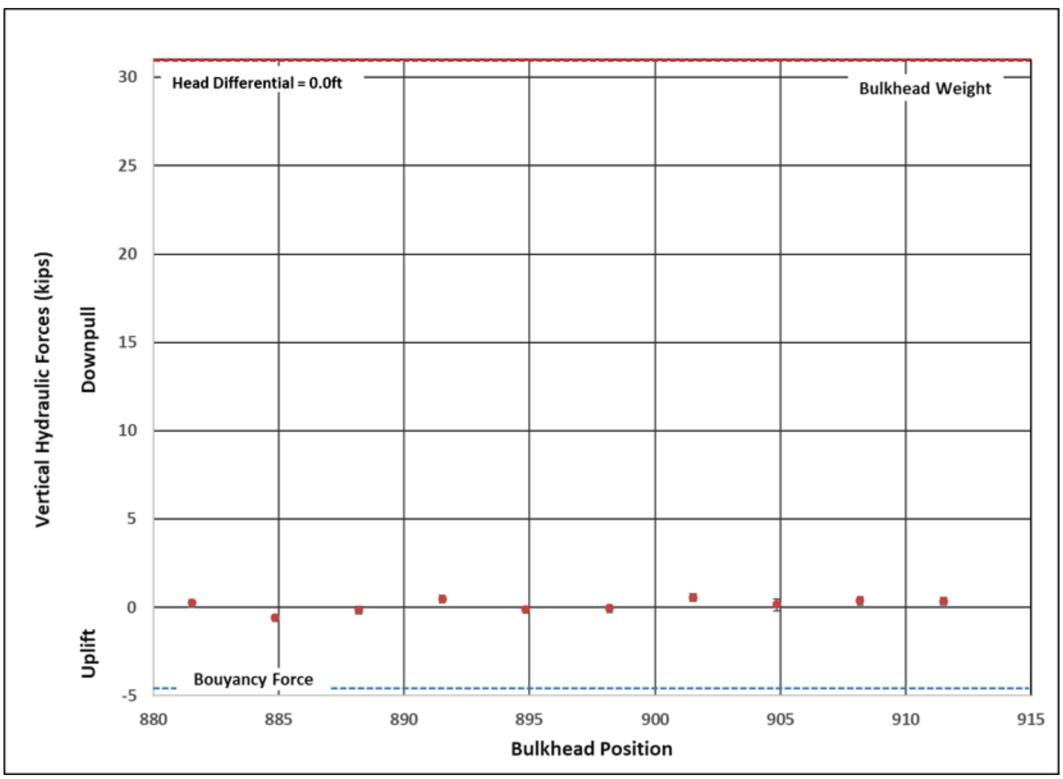


Figure 57. Second bulkhead 20-year event (all gates open) vertical hydraulic forces.

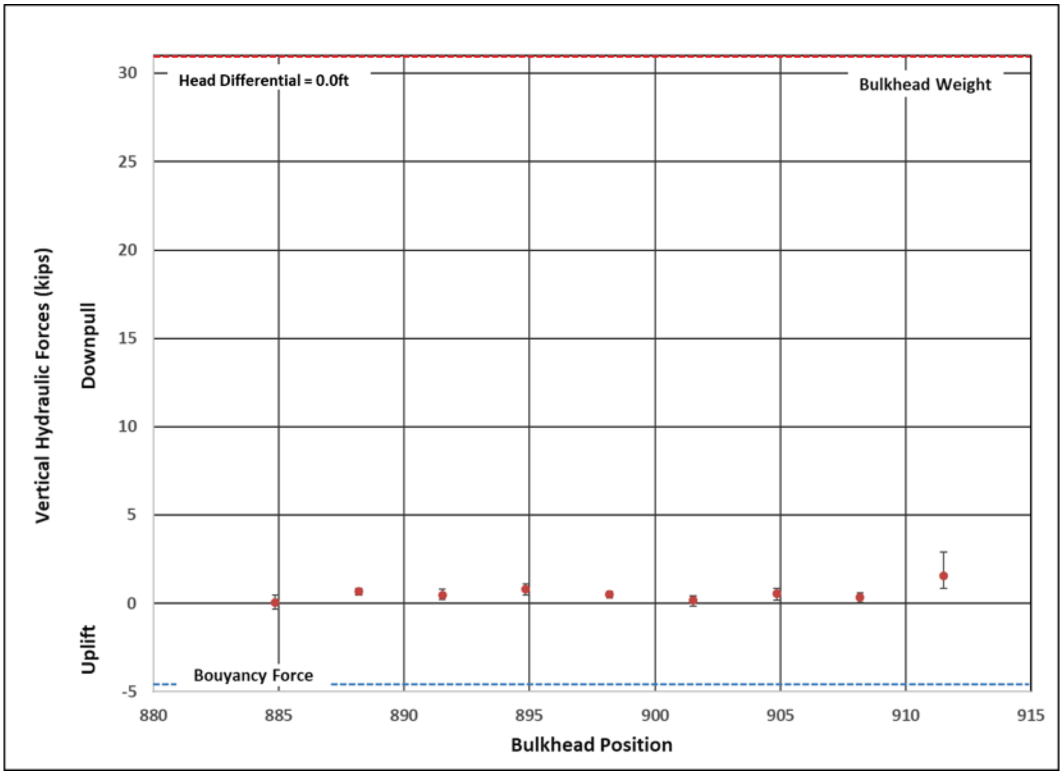


Figure 58. Third bulkhead 20-year event (all gates open) vertical hydraulic forces.

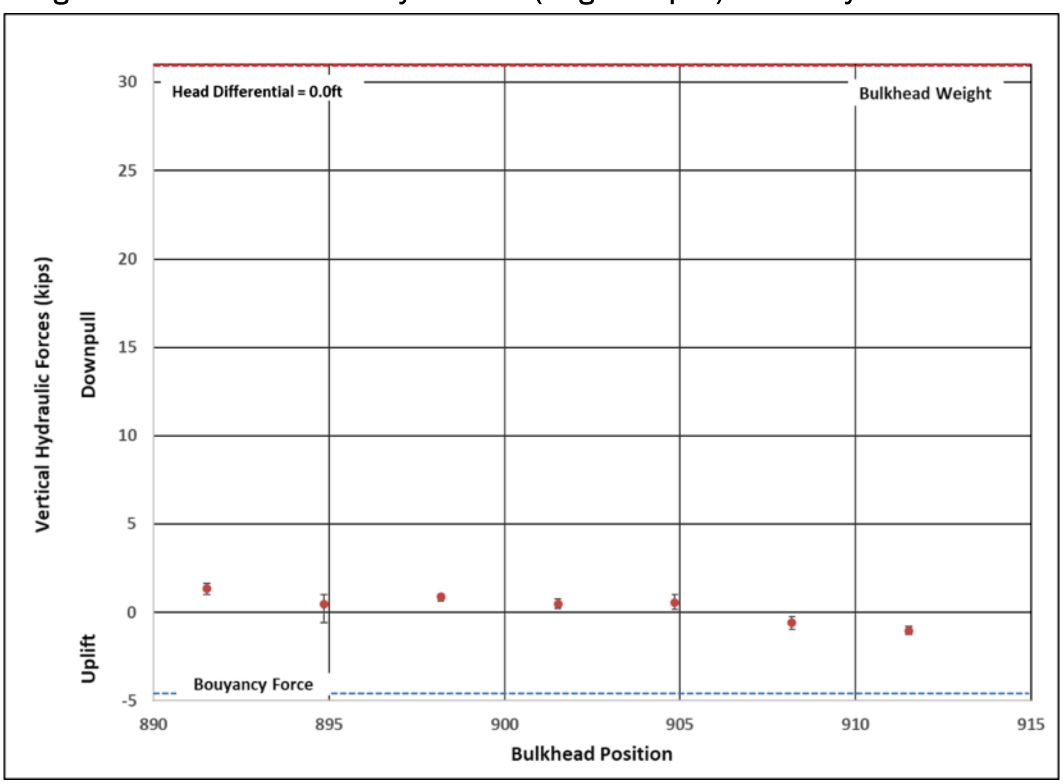


Figure 59. Fourth bulkhead 20-year event (all gates open) vertical hydraulic forces.

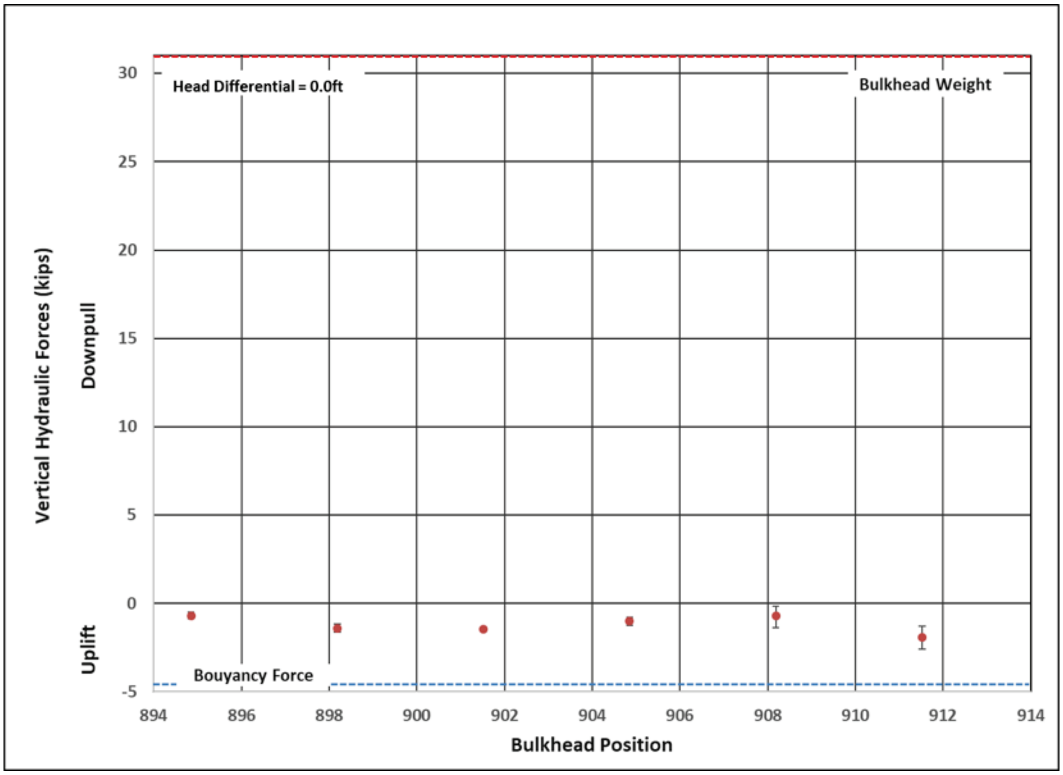


Figure 60. Fifth bulkhead 20-year event (all gates open) vertical hydraulic forces.

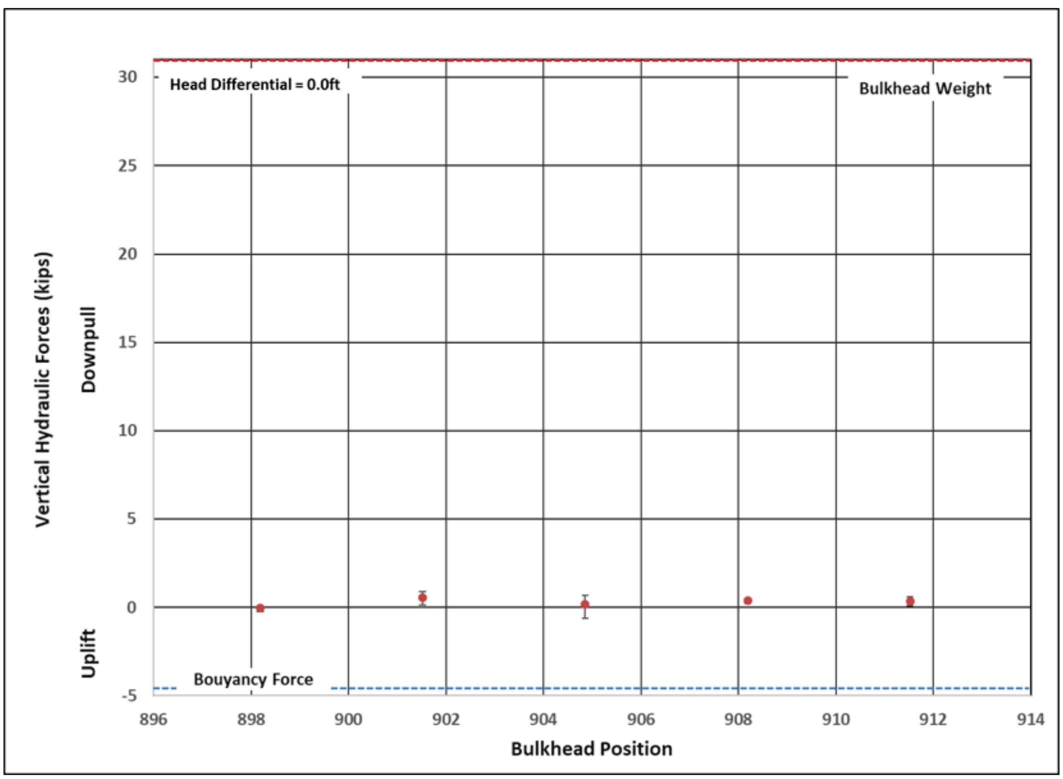
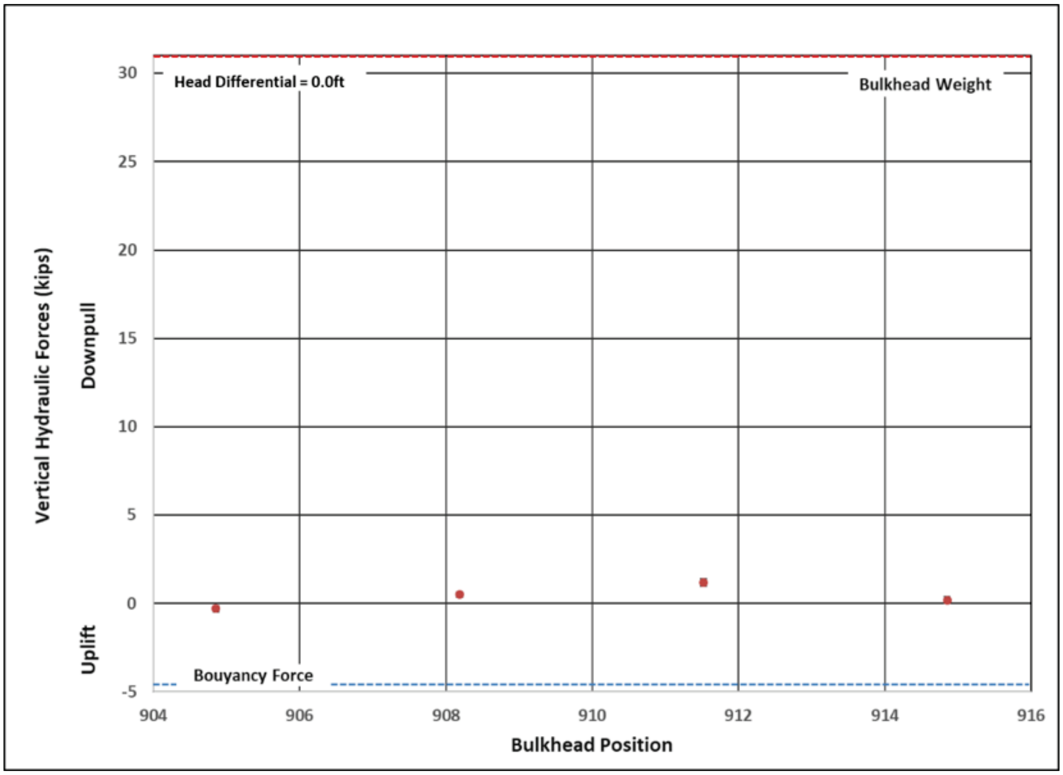


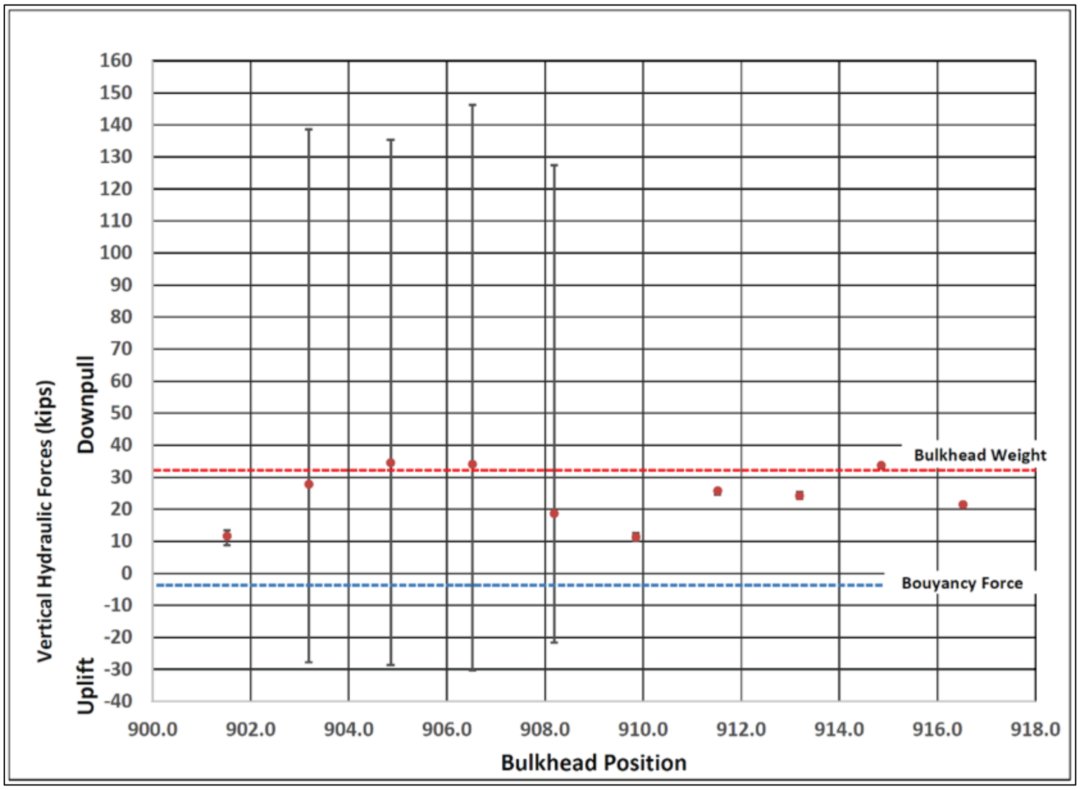
Figure 61. Sixth bulkhead 20-year event (all gates open) vertical hydraulic forces.



Appendix C: 50-year Event Test Results

Figure 62 presents the data that were collected during the 50-year event (note the downpull forces reaching the 145 – 150 kip range).

Figure 62. First bulkhead 50-year event (east and west gates closed) vertical hydraulic forces.



Unit Conversion Factors

Multiply	By	To Obtain
feet	0.3048	meters
inches	0.0254	meters
miles (US statute)	1,609.347	meters
US fluid ounces	29.57	milliliters

Acronyms and Abbreviations

3D	three-dimensional
AEP	annual exceedance probability
DIS	Diversion Inlet Structure
FMM	Fargo-Moorhead Metropolitan
MVP	St. Paul District
PMF	Probable Maximum Flood
RSS	Red River Structure
USACE	US Army Corps of Engineers
WSE	water surface elevation
WWRS	Wild Rice River Structure

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MIPR 3122-20/XX-2429, “Fargo-Moorhead Metropolitan Area Flood Risk Management Project: Red River Structure Physical Model Bulkhead Testing”

14. ABSTRACT
The US Army Corps of Engineers, St. Paul District, and its non-federal sponsors are designing and constructing a flood risk management project that will reduce the risk of flooding in the Fargo-Moorhead metropolitan area. There is a 30-mile long diversion channel around the west side of the city of Fargo, as well as a staging area that will be formed upstream of a 20-mile long dam (referred to as the Southern Embankment) that collectively includes an earthen embankment with three gated structures: the Diversion Inlet Structure, the Wild Rice River Structure, and the Red River Structure (RRS). A physical model has been constructed and analyzed to assess the hydraulic conditions near and at the RRS for verification of the structure’s flow capacity as well as optimization of design features for the structure. This report describes the modeling techniques and instrumentation used in the investigation and details the evaluation of the forces exerted on the proposed bulkheads during emergency operations for the RRS.

15. SUBJECT TERMS
Bulkheads, Fargo (N.D.), Flood control, Hydraulic models, Hydraulic structures, Moorhead (Minn.), Red River of the North

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