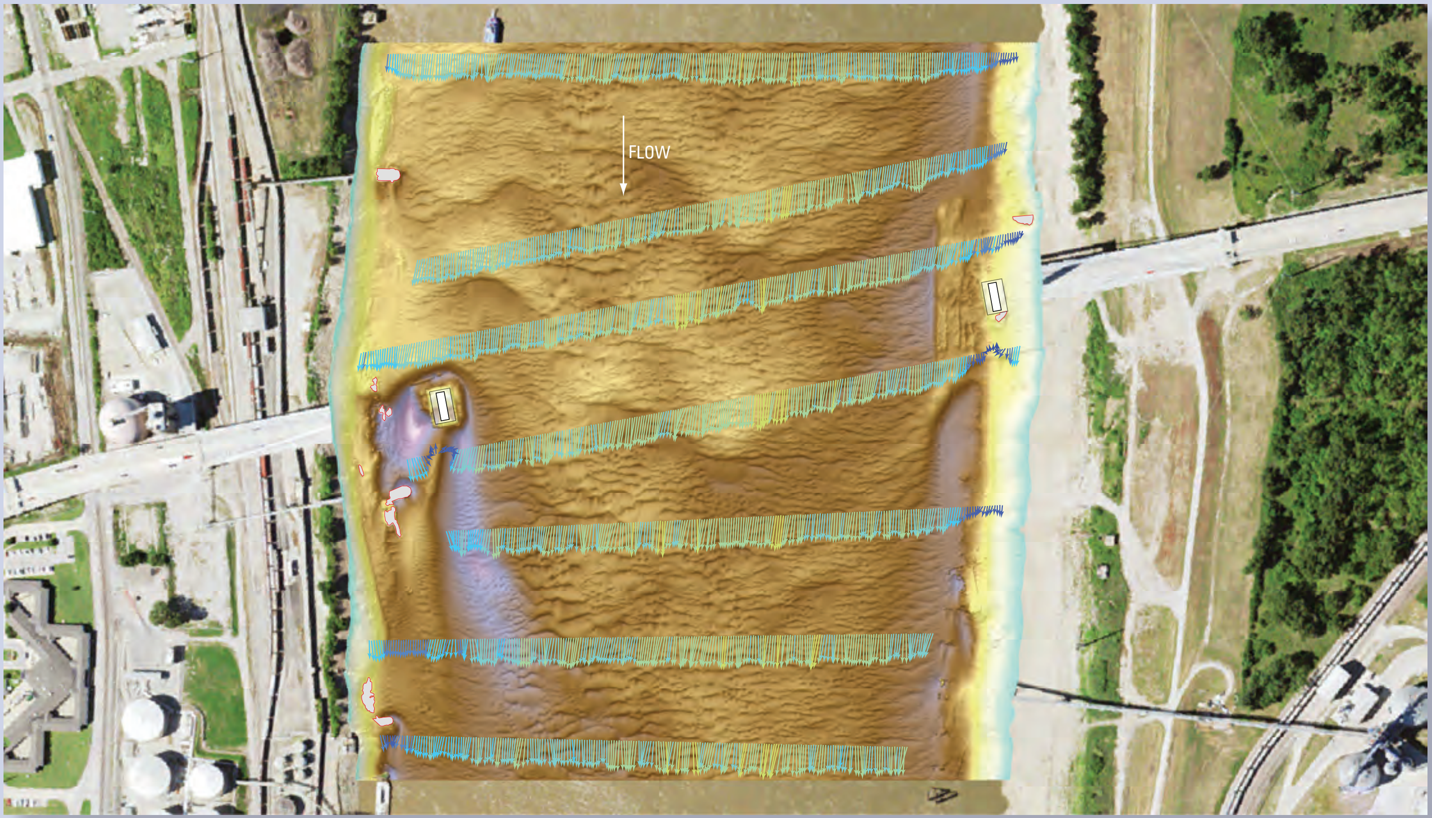
Prepared in cooperation with the Missouri Department of Transportation

Bathymetric and Velocimetric Surveys at Highway Bridges Crossing the Missouri and Mississippi Rivers near St. Louis, Missouri, May 23–27, 2016



Scientific Investigation Report 2017–5076

U.S. Department of the Interior
U.S. Geological Survey

Cover. Bathymetry and vertically averaged velocities of the Mississippi River channel near structure A6500 on Interstate 70 in St. Louis, Missouri, on May 25, 2016.

Back cover. Top: Point cloud visualization of the channel bed and right (west) side of main channel pier 11 of structure A6500 on Interstate 70 crossing the Mississippi River in St. Louis, Missouri, on May 25, 2016. Bottom: The U.S. Geological Survey boat surveying bathymetry and velocimetry at structures A4936 and A1850 on Interstate 255 crossing the Mississippi River near St. Louis, Missouri, on May 26, 2016.

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U.S. Department of the Interior
RYAN K. ZINKE, Secretary

U.S. Geological Survey
William H. Werkheiser, Acting Director

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
cubic yard (yd^3)	0.7646	cubic meter (m^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Supplemental Information

In this report, the words “left” and “right” generally refer to directions that would be reported by an observer facing downstream.

Distance on the Missouri River is given in river miles (RM) upstream from the confluence with the Mississippi River at St. Louis, Missouri, at river mile 195.2 of the Upper Mississippi River.

Distance on the Mississippi River is given in river miles (RM) upstream from the confluence with the Ohio River at Cairo, Illinois, at river mile 953.5 of the Lower Mississippi River.

Frequency is given in kilohertz (kHz).

Data were collected, processed, and output in the International System of Units, and converted to U.S. customary units for presentation in the report at the request and for the convenience of the cooperator.

Abbreviations

ADCP	acoustic Doppler current profiler
CUBE	Combined Uncertainty Bathymetric Estimator
GGA	shorthand for the $GPGGA standard output format for Global Navigation Satellite System (GNSS) essential fix data defined by the National Marine Electronics Association (NMEA)-0183 standard that includes information on the three-dimensional location and accuracy of the GNSS receiver (National Marine Electronics Association, 2002)
GNSS	Global Navigation Satellite System
IMU	inertial measurement unit
INS	inertial navigation system
MBES	multibeam echosounder (the sonar system)
MBMS	multibeam echosounder mapping system (the sonar, navigation, and data acquisition system)
MMS™	POS-Pac™ Mobile Mapping Suite (the navigation solution post-processing software)
MoDOT	Missouri Department of Transportation
NMEA	National Marine Electronics Association
POS MV™	Position Orientation Solution for Marine Vessels (the inertial navigation system)
RTK	real-time kinematic (a type of differential correction for navigation with GNSS)
RTN	real-time network
SBET	smoothed best estimate of trajectory (a postprocessed navigation solution)
TIN	triangulated irregular network
TPU	total propagated uncertainty
USGS	U.S. Geological Survey
VMT	Velocity Mapping Toolbox (Parsons and others, 2013)

Bathymetric and Velocimetric Surveys at Highway Bridges Crossing the Missouri and Mississippi Rivers near St. Louis, Missouri, May 23–27, 2016

By Richard J. Huizinga

Abstract

Bathymetric and velocimetric data were collected by the U.S. Geological Survey, in cooperation with the Missouri Department of Transportation, near 13 bridges at 8 highway crossings of the Missouri and Mississippi Rivers in the greater St. Louis, Missouri, area from May 23 to 27, 2016. A multibeam echosounder mapping system was used to obtain channel-bed elevations for river reaches ranging from 1,640 to 1,970 feet longitudinally and extending laterally across the active channel from bank to bank during low to moderate flood flow conditions. These bathymetric surveys indicate the channel conditions at the time of the surveys and provide characteristics of scour holes that may be useful in the development of predictive guidelines or equations for scour holes. These data also may be useful to the Missouri Department of Transportation as a low to moderate flood flow comparison to help assess the bridges for stability and integrity issues with respect to bridge scour during floods.

Bathymetric data were collected around every pier that was in water, except those at the edge of water, and scour holes were observed at most surveyed piers. The observed scour holes at the surveyed bridges were examined with respect to shape and depth.

The frontal slope values determined for scour holes observed in the current (2016) study generally are similar to recommended values in the literature and to values determined for scour holes in previous bathymetric surveys. Several of the structures had piers that were skewed to primary approach flow, as indicated by the scour hole being longer on the side of the pier with impinging flow, and some amount of deposition on the leeward side, as typically has been observed at piers skewed to approach flow; however, at most skewed piers in the current (2016) study, the scour hole was deeper on the leeward side of the pier. At most of these piers, the angled approach flow was the result of a deflection or contraction of flow caused by a spur dike near the pier, which may affect flow differently than for a simple skew. At structure A6500 (site 33), the wide face of the pier footing and seal course would behave as a complex foundation, for which scour is computed differently.

Previous bathymetric surveys exist for all the sites examined in this study. A previous survey in October 2010 at most of the sites had similar flow conditions and similar results to the 2016 surveys. A survey during flood conditions in August 2011 at the sites on the Missouri River and in May 2009 at structures A4936 and A1850 (site 35) on the Mississippi River did not always indicate more substantial scour during flood conditions. At structure A6500 (site 33) on the Mississippi River, a previous survey in 2009 was part of a habitat assessment before construction of the bridge and provides unique insight into the effects of the construction of that bridge on the channel in this reach. Substantial scour was observed near the right pier, and the riprap blanket surrounding the left pier seems to limit scour near that pier. Multiple additional surveys have been completed at structures A4936 and A1850 (site 35) on the Mississippi River, and the results of these surveys also are presented.

Introduction

Scour in alluvial channels is the removal of channel bed and bank material by flowing water and is the leading cause of bridge failures in the United States (Richardson and Davis, 2001). Scour at a bridge site is the result of short- and long-term geomorphic processes and the local effects caused by elements of the structure in or adjacent to the waterway (Richardson and Davis, 2001; Huizinga and Rydlund, 2004). Because the effects of scour can be severe and dangerous, bridges and other structures over waterways are routinely assessed and inspected. Scour processes can be exacerbated during high-flow conditions because velocity and depth typically increase.

The Missouri Department of Transportation (MoDOT) is responsible for most of the transportation infrastructure in the State. A part of this responsibility is fulfilled through periodic inspections of highway structures, including bridges that span waterways. At most of these structures, all or most of the structure can be fully inspected from land or from personnel lift trucks deployed from the roadway of the structure; however, for structures over primary waterways, such as the Missouri and Mississippi Rivers, inspection of the part of the bridge that is underwater requires a different approach.

The U.S. Geological Survey (USGS), in cooperation with MoDOT, began assessing scour at waterway crossings throughout the State in 1991 (Huizinga and Rydlund, 2004). In 2007, the USGS, in cooperation with MoDOT, began determining channel bathymetry and monitoring bridges for scour using single-beam echosounders and a multibeam echosounder mapping system (MBMS; Rydlund, 2009; Huizinga, 2010, 2011, 2013, 2014, 2015, 2016; Huizinga and others, 2010). In particular, the MBMS has proven to be a useful tool not only in determining channel bathymetry but also in providing a medium- to high-resolution representation of bridge structural elements below the water line. In 2010, the USGS, in cooperation with MoDOT, began collecting bathymetric data at various highway bridges across primary waterways in Missouri. In March 2010, 9 highway bridges at 7 crossings over the Missouri River near Kansas City, Missouri, were assessed using the MBMS (Huizinga, 2010); and in October 2010, 12 highway bridges at 7 crossings over the Missouri and Mississippi Rivers near St. Louis, Mo., were assessed (Huizinga, 2011). During high-flow conditions in June–August 2011, many of the highway bridges and several of the railroad bridges along the entirety of the Missouri River downstream from Montana were assessed (Densmore and others, 2013; Dietsch and others, 2014), including the 37 highway bridges (at 28 crossings) that span the Missouri River in and into Missouri (Huizinga, 2012). In April and May 2013, 10 highway bridges at 9 crossings over the Missouri River between Kansas City and St. Louis, Mo., were assessed as part of more routine, nonflood surveys at bridge sites in and into Missouri (Huizinga, 2014). In June 2014, eight highway bridges at seven crossings over the Missouri and Mississippi Rivers on the periphery of Missouri also were assessed as part of the routine, nonflood surveys at bridge sites (Huizinga, 2015). In June 2015, eight of the highway bridges at seven of the crossings near Kansas City were surveyed again (Huizinga, 2016).

The current (2016) study is the second round of routine, nonflood surveys at the highway bridges across the Missouri and Mississippi Rivers near St. Louis, Mo. (fig. 1), and includes 13 bridges at 8 crossings (table 1). One of the bridges at one crossing that was part of the previous surveys in St. Louis (structure J1000 on U.S. Highway 40; Huizinga, 2011, 2012) recently was replaced, resulting in structure A4017 being made the westbound bridge and a new structure A7577 being added as the new eastbound bridge (table 1); furthermore, the new Stan Musial Veterans Memorial bridge on Interstate 70 (structure A6500; table 1) also is included in the current study, the proposed location of which was the subject of an aquatic habitat evaluation with MoDOT in 2009 before construction (Huizinga and others, 2010).

Purpose and Scope

The purpose of this report is to document the results of bathymetric and velocimetric surveys completed in 2016 of the Missouri and Mississippi River channels near 13 highway bridges at 8 crossings in the greater St. Louis, Mo., metropolitan area (fig. 1) using a MBMS and an acoustic Doppler current profiler (ADCP; table 1). Equipment and methods used and results obtained are described. The results obtained from the bathymetric and velocimetric surveys of the channel document the channel-bed conditions and velocity distribution at the time of the surveys and provide characteristics of scour holes that may be useful in developing predictive guidelines or equations for scour holes. These data also may be used by MoDOT as a low to moderate flood flow comparison to help assess the bridges for stability and integrity issues with respect to bridge scour. Comparison of results to previous surveys at the sites (Huizinga, 2011, 2012; Huizinga and others, 2010) also are provided.

Description of Study Area

The study area for this report is the Missouri and Mississippi Rivers in St. Louis, Mo., and includes the City of St. Louis, St. Louis County, and parts of St. Charles and Jefferson Counties (fig. 1). The Missouri River flows through the St. Louis metropolitan area from west to east, joining the Mississippi River north of downtown St. Louis. The Missouri and Mississippi Rivers are channelized in the St. Louis metropolitan area; rock revetment, spur dikes, and L-head dikes are present along the banks to maintain the channel alignment, and levees and floodwalls are present on the upper banks to limit flooding in the industrial, commercial, residential, and agricultural areas on the flood plains. The site numbering sequence used in previous studies on the Missouri and Mississippi Rivers (Huizinga, 2012, 2015) is used in this report for consistency and comparability.

Description of Flow Conditions

Data from the streamflow-gaging station (hereinafter referred to as “streamgage”) on the Missouri River at St. Charles, Mo. (station 06935965; U.S. Geological Survey, 2017; fig. 1), indicates the Missouri River was between flood rises when the sites on the Missouri River were surveyed on May 23–27, 2016 (fig. 2*A*); however, the trough happened during generally higher late-spring flows (fig. 2*B*), during low to moderate flood flow conditions of nearly 150,000 cubic feet per second (ft^3/s), compared to 60,000–65,000 ft^3/s observed during troughs in early April and late August. Similarly, data from the streamgage on the Mississippi River at St. Louis, Mo. (station 07010000; U.S. Geological Survey, 2017; fig. 1), indicates the Mississippi River also was between flood rises when the sites on the Mississippi River were surveyed May 25–26, 2016 (fig. 2*A*), but was during generally higher late-spring flows (fig. 2*B*).

The discharge on the Missouri River as measured at the St. Charles streamgage ranged from about 134,000 to 152,000 ft^3/s during the dates of the surveys. This discharge range has a daily exceedance probability range of about 14 to

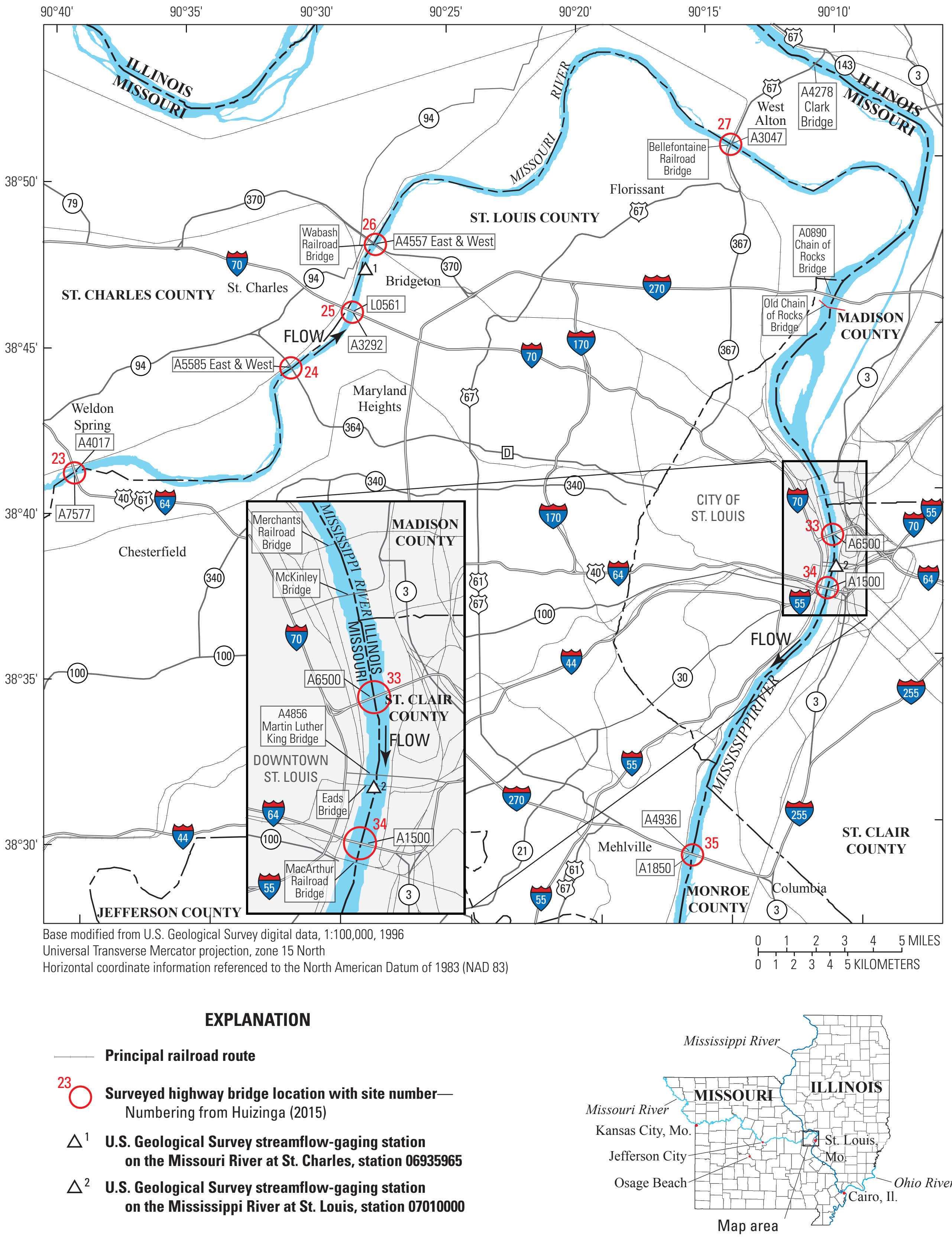


Figure 1. Location of surveyed bridges crossing the Missouri and Mississippi Rivers in the St. Louis, Missouri, metropolitan area.

Table 1. Highway bridges crossing the Missouri and Mississippi River in and into Missouri in the St. Louis metropolitan area, in downstream order.

[MoDOT, Missouri Department of Transportation; US, U.S. highway; E, eastbound; W, westbound; MO, Missouri State highway; IS, Interstate highway; —, not known/applicable; IDOT, Illinois Department of Transportation; S, southbound; N, northbound; shaded rows are those bridges surveyed for this study]

Site number (fig. 1)	Primary agency	Structure number	Local name	County	Route	River	River mile[a]	Surveyed as part of this study	Remarks	Figures
23	MoDOT	A7577	Daniel Boone	St. Charles, Mo.	US 40 E	Missouri	43.9	Yes	Dual bridge crossing with A4017	1, 6–8, 10–12, 60–62, and appendix 1–1
		A4017	Daniel Boone	St. Louis, Mo.	US 40 W			Yes	Dual bridge crossing with A7577	1, 6–7, 9–12, 60–62, and appendix 1–1
24	MoDOT	A5585 E	Page Avenue	St. Charles, Mo.	MO 364 E	Missouri	32.7	Yes	Dual bridge crossing	1, 13–15, 17–19, 60–62, and appendix 1–2
		A5585 W	Page Avenue	St. Louis, Mo.	MO 364 W			Yes	Dual bridge crossing	1, 13–14, 16–19, 60–62, and appendix 1–2
25	MoDOT	A3292	Blanchette	St. Charles, Mo.	IS 70 E	Missouri	29.6	Yes	Dual bridge crossing with L0561	1, 20–23, 25–26, 60–61, 63, and appendix 1–3
		L0561	Blanchette	St. Louis, Mo.	IS 70 W			Yes	Dual bridge crossing with A3292	1, 20–22, 24–26, 60–61, 63, and appendix 1–3
26	MoDOT	A4557 E	Discovery	St. Charles, Mo.	MO 370 E	Missouri	27.0	Yes	Dual bridge crossing	1, 27–30, 32–33, 60–61, 63, and appendix 1–4
		A4557 W	Discovery	St. Louis, Mo.	MO 370 W			Yes	Dual bridge crossing	1, 27–29, 31–33, 60–61, 63, and appendix 1–4
27	MoDOT	A3047	Lewis & Clark	St. Charles, Mo.	US 67	Missouri	8.1	Yes	—	1, 34–39, 60–61, 63, and appendix 1–5
—	IDOT	A4278	Clark	St. Charles, Mo.	US 67	Mississippi	202.6	No	—	1
—	IDOT	A0890	Chain of Rocks	St. Louis City, Mo.	IS 270	Mississippi	190.8	No	—	1
—	IDOT	—	McKinley	St. Louis City, Mo.	—	Mississippi	182.6	No	—	1
33	MoDOT	A6500	Stan Musial Veterans Memorial	St. Louis City, Mo.	IS 70	Mississippi	181.2	Yes	—	1, 5, 40–45, 60–61, 64, and appendix 1–6
—	IDOT	A4856	Martin Luther King	St. Louis City, Mo.	—	Mississippi	180.2	No	—	1
—	St. Louis	—	Eads	St. Louis City, Mo.	—	Mississippi	180.0	No	—	1
34	MoDOT	A1500	Poplar Street	St. Louis City, Mo.	IS 55	Mississippi	179.2	Yes	—	1, 46–50, 60–61, 64, and appendix 1–7
35	MoDOT	A4936	Jefferson Barracks	St. Louis, Mo.	IS 255 S	Mississippi	168.8	Yes	Dual bridge crossing with A1850	1, 51–53, 55–61, 64, and appendixes 1–8, 1–9
		A1850	Jefferson Barracks		IS 255 N			Yes	Dual bridge crossing with A4936	1, 51–52, 54–61, 64, and appendixes 1–8, 1–9

[a]For sites 23–27, river mile is the distance upstream on the Lower Missouri River, starting at the confluence with the Mississippi River at St. Louis, Mo. (fig. 1), at river mile 195.2 of the Upper Mississippi River. For sites 33–35, river mile is the distance upstream on the Upper Mississippi River, starting at the confluence with the Ohio River at Cairo, Ill. (fig. 1), at river mile 953.5 of the Lower Mississippi River.

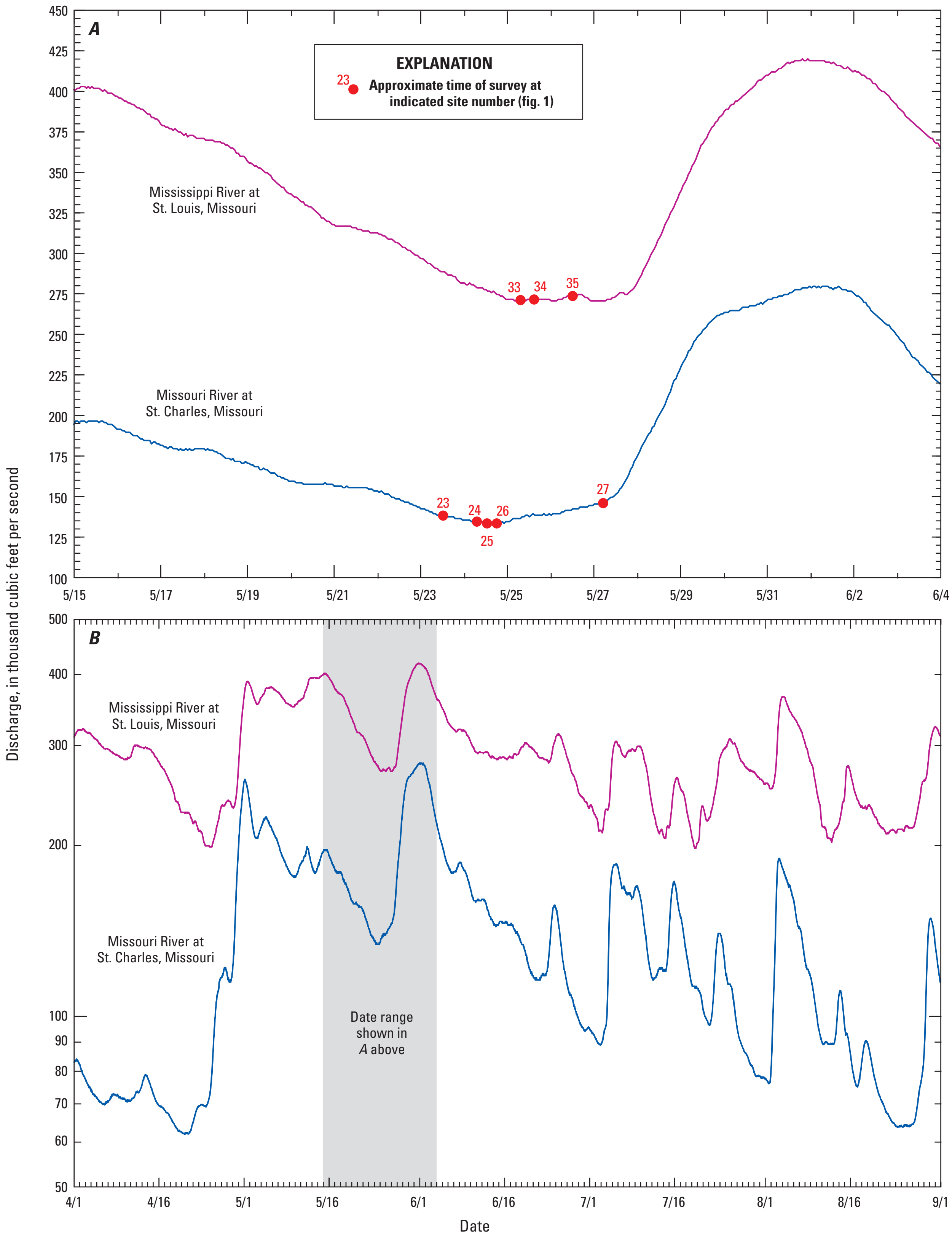


Figure 2. Unit values of discharge (1-hour interval) from the streamflow-gaging stations on the Missouri River at St. Charles, Missouri (station 06935965), and on the Mississippi River at St. Louis, Missouri (station 07010000; U.S. Geological Survey, 2017). *A*, May 15 through June 4, 2016. *B*, April 1 through September 1, 2016.

19 percent (based on flow duration analysis; U.S. Geological Survey, 2003) and is less than the 50-percent annual exceedance probability (2-year recurrence interval) flood discharge of 250,000 ft^3/s (U.S. Army Corps of Engineers, 2003b, plate E–20). The discharge on the Mississippi River as measured at the St. Louis streamgage ranged from about 271,000 to 290,000 ft^3/s during the dates of the surveys. This discharge range has a daily exceedance probability range of about 20 to 22 percent (based on flow duration analysis; U.S. Geological Survey, 2003) and is less than the 50-percent annual exceedance probability (2-year recurrence interval) flood discharge of 450,000 ft^3/s (U.S. Army Corps of Engineers, 2003a, table D–28).

Flow conditions at or less than the 50-percent annual exceedance probability (2-year recurrence interval) flood are in the low to moderate flood-flow regime. In an analysis of real-time scour monitor data at Jefferson City, Mo., Huizinga (2014) noted that substantial pier scour begins soon after the onset of hydrograph rise (substantial rise of 8 feet [ft] or more), although the scour often does not reach maximum depth until the peak stage is reached or sometime thereafter (Huizinga, 2014, fig. 35). Although the peak discharge for the late spring happened shortly after the surveys, several moderate peaks had been observed at both streamgages, and flow was substantially higher than base flow based on the daily exceedance values during the surveys (fig. 2*B*). Although the scour scenario captured at the sites in this study may not represent the maximum scour potential at the sites, the cumulative information gathered at several sites during the course of multiple surveys in 2010, 2011, and 2016 remains useful for determining scour for a variety of flow conditions, particularly when combined with, or compared to, a scour scenario captured at high flood flow conditions.

Description of Equipment and Basic Processing

The bathymetry of the Missouri and Mississippi Rivers at each of the bridges was determined using a high-resolution MBMS. The various components of the MBMS used for this study are as described in reports about studies on the Missouri and Mississippi Rivers in Missouri (Huizinga, 2010, 2011, 2012, 2013, 2014, 2015, 2016; Huizinga and others, 2010) and on the Missouri and Yellowstone Rivers in North Dakota (Densmore and others, 2013). The survey methods used to obtain the data were similar to these previous studies, as were the measures used to ensure data quality. A brief description of the equipment follows; a complete description of the various system components and methods used in this study is available in the previous reports by Huizinga (2010), Huizinga and others (2010), and Densmore and others (2013).

A MBMS is an integration of several individual components: the multibeam echosounder (MBES), an inertial navigation system (INS), and a data-collection and data-processing computer. The MBES that was used for the 2016 surveys is the Teledyne RESON SeaBat® 7125-SV2 (fig. 3), operated at a frequency of 400 kilohertz (kHz). The INS that was used is the Applanix Position Orientation Solution for Marine Vessels (POS MV™) WaveMaster system. The INS provides position in three-dimensional space and measures the heave, pitch, roll, and heading of the vessel (and, thereby, the MBES) to accurately position the data received by the MBES. Real-time kinematic (RTK) differential corrections for the INS came from cellular communication with the MoDOT Global Navigation Satellite System (GNSS) real-time network (RTN) for the navigation and tide solution during the 2016 surveys.

As in previous surveys (Huizinga, 2010, 2011, 2012, 2013, 2014, 2015, 2016), the navigation information from the 2016 surveys was postprocessed using the POS-Pac™ Mobile Mapping Suite (MMS™) software (Applanix Corporation, 2009) to mitigate the effects of degraded positional accuracy of the vessel while near or under a bridge. POS-Pac™ MMS™ provides tools to identify and compensate for sensor and environmental errors and computes an optimally blended navigation solution from the GNSS and inertial measurement unit (IMU) raw data. The blended navigation solution (called a "smoothed best estimate of trajectory" or "SBET" file) generated by postprocessing the navigation data was applied to the survey at a given bridge to minimize the effects of the GNSS outages while surveying under the bridges.

The data from the MBES and INS components were processed and integrated into a cohesive dataset for cleanup and visualization. A computer onboard the survey vessel ran the HYPACK®/HYSWEEP® data acquisition software (HYPACK, Inc., 2015) that was used to prepare for the bathymetric surveys and collect the survey data. After completing the surveys, the acquired depth data were further processed to remove data spikes and other spurious points in the multibeam swath trace, georeferenced using the navigation and position solution data from the SBET file from POS-Pac™ MMS™, and visualized in HYPACK®/HYSWEEP® as a triangulated irregular network (TIN) surface or a point cloud. The georeferenced data were output to a comma-delimited file, either having no data reduction or filtered and reduced to a 1.64-ft data resolution. These comma-delimited data were compiled into a geographic information system database for each site using the ArcGIS package (Esri, 2013), and are included with metadata in Huizinga (2017).

Information about the velocity of the river at various points throughout each study reach were collected using an ADCP, similar to recent previous studies by Huizinga (2012, 2013, 2014, 2015, 2016). A Teledyne RD Instruments Rio Grande ADCP operating at 600 kHz was used to obtain velocities at 1.64-ft increments, or "bins," throughout the water column. The Rio Grande 600 kHz ADCP operates in depths from 2.3 to 230 ft and determines the velocity of the water by measuring the Doppler shift of an acoustic signal reflected from various particles suspended in the water (Mueller and others, 2013). By measuring the Doppler shift in four different beam directions, the velocity of the water in each bin can be determined in three dimensions.

Figure 3. The Teledyne RESON SeaBat® 7125-SV2 multibeam echosounder. *A*, viewed from the bottom. *B*, mounted on the port side of the U.S. Geological Survey boat.

Basic Description of Methods

The methods used to acquire and ensure the collection of quality data were the same as those used in previous studies using the MBES (methods are detailed in Huizinga, 2010, 2012; Huizinga and others, 2010). A brief summary of—and differences from—these methods are highlighted below.

Surveying Methods

Generally, the surveyed area extended across the active channel from bank to bank, as had been done in the previous studies on the Missouri and Mississippi Rivers near St. Louis (Huizinga, 2011, 2012). The surveyed reaches ranged from 1,640 to 1,970 ft long in the direction of flow, positioned so that the surveyed highway bridges were about one-third to one-half of the total length from the upstream boundary, using about the same upstream and downstream boundaries as were used in the 2011 flood study (Huizinga, 2012). The upstream and downstream boundaries of the surveyed areas were assumed to be beyond the substantial hydraulic effects (wake vortices and shear flow) of the bridge structures.

As in previous studies, bathymetric data were obtained along longitudinal transect lines, and each survey was designed so that there was overlap of the survey swaths to attempt to ensure complete coverage of the channel bed and minimize sonic "shadows." Substantial overlap was achieved for many of the surveyed swaths, except in shallow areas near the channel banks or spur dikes, and near in-flow structures, debris rafts, or moored barges. The presence of debris rafts and moored barges made surveying difficult in some areas. Areas near the bridge piers and along the banks also were surveyed in an upstream direction with the MBES head tilted at either 30 degrees to port or starboard to increase the acquisition of bathymetric data in the shallow areas, and higher on the banks and the sides of the piers. To limit potential damage to the MBES head, most of the shallow areas (less than about 6 ft of water depth) were not surveyed.

After completing the bathymetric survey with the MBMS at a given site, the velocity data were obtained with the ADCP on seven lateral sections across the channel within the study area. The position and speed of the boat was determined using a differential GNSS receiver mounted on a pole directly above the ADCP. The bottom-track reference method for determining boat speed was anticipated to be unusable because of moving channel-bed material, so the boat velocity was determined using the GNSS essential fix (GGA) National Marine Electronics Association (NMEA)–0183 sentence (National Marine Electronics Association, 2002) from the differential GNSS receiver. The distance between the velocity section lines generally was about 260 ft. Three sections were upstream and four sections were downstream from the bridge in question. Each section line was traversed in each direction across the river. The reported velocity values are the average from the two traverses of a given section line, using averaging algorithms from the Velocity Mapping Toolbox (VMT; Parsons and others, 2013). Discharge for a site was computed as the average of the discharges from reciprocal pairs (two transects per section line) at the various sections in the reach. Generally, measured discharge for an individual transect was within 5 percent of the average.

Survey Quality-Assurance/Quality-Control Measures

A quality-assurance plan has been established for discharge measurements using ADCPs that includes several instrument diagnostic checks and calibrations. These standard operating procedures were followed when acquiring the velocity profile data for these surveys, including a moving-bed test. For a detailed discussion of these procedures, see Mueller and others (2013).

For the MBMS, the principal quality-assurance measures were assessed in real time during the survey. The MBMS operator continuously assessed the quality of the collected data during the survey by making visual observations of across-track swaths (such as convex, concave, or skewed bed returns in flat, smooth bottoms), noting data quality flags and alarms from the MBES and the INS, and noting comparisons between adjacent overlapping swaths. In addition to the real-time quality-assurance assessments during the survey, beam angle checks and a suite of patch tests were executed to ensure quality data were acquired from the MBMS before the 2016 surveys. These tests were completed at the Lake of the Ozarks near Osage Beach, Mo. (fig. 1, index map). Additional patch tests were completed on the last day of the 2016 surveys, on the Missouri River near St. Louis, to check that the mounting angles had not moved during the surveys.

Beam Angle Check

A beam angle check is used to determine the accuracy of the depth readings obtained by the outer beams (greater than 25 degrees from nadir [vertical]) of the MBES (U.S. Army Corps of Engineers, 2013), which may change with time as a result of inaccurate sound velocities, physical configuration changes, and overall depth being surveyed. The HYPACK®/HYSWEEP® software has a utility that develops a statistical assessment of the quality of the outer beams compared to a reference surface (HYPACK, Inc., 2015). On March 29, 2016, a reference surface was surveyed for a part of the Lake of the Ozarks near Osage Beach (fig. 1, index map), and check lines were run across the reference surface. Included with the measurement was a sound-velocity profile cast to document and quantify any stratification in the water column near the reference surface. The results of this beam angle check (table 2) were within the recommended performance standards used by the U.S. Army Corps of Engineers for hydrographic surveys for all the representative angles below 50 degrees (U.S. Army Corps of Engineers, 2013), permitting the use of the central 90 degrees of the sound navigation and ranging (sonar) swath with confidence.

Ideally, the average depth of the reference surface used in the beam angle check would be equal to or greater than the depth in the area being surveyed. The depth of the Missouri and Mississippi Rivers in each study reach generally was impossible to estimate before each survey because of the dynamic nature of the channel bed and flow conditions; however, the average depth of the reference surface (about 53 ft) was expected to be greater than the average depth observed in the 2016 surveys because the average depths observed during the previous surveys in the St. Louis area generally were less than 40 ft (the average depth is the difference between the average water surface elevation and average channel-bed elevation in Huizinga [2012, table 5]). As described earlier in the “Surveying Methods” section in this report, areas with depths greater than the average depths generally had substantial overlap of the surveyed swath with adjacent swaths. Data from the outer beams in these areas were able to be either verified or removed to mitigate any detrimental effects caused by beam angle inaccuracies.

Table 2. Results of a beam angle check from two check lines over a reference surface at the Lake of the Ozarks near Osage Beach, Missouri, on March 29, 2016.

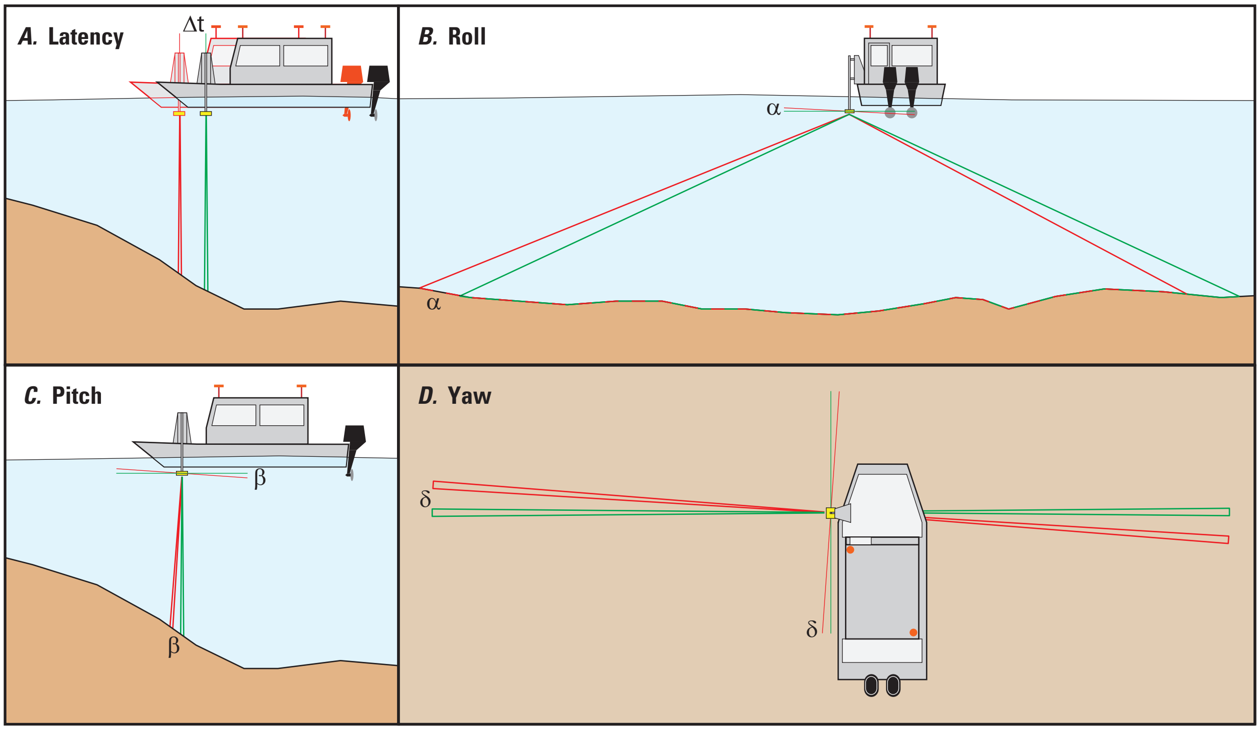
[<, less than; —, no data]

Beam angle limit (degree)	Maximum outlier (foot)	Mean difference (foot)	Standard deviation (foot)	95-percent confidence (foot)
0	0.46	–0.07	0.10	0.16
5	0.52	–0.07	0.10	0.16
10	0.39	–0.07	0.10	0.16
15	0.33	–0.07	0.10	0.16
20	0.49	–0.03	0.10	0.20
25	0.62	–0.03	0.10	0.16
30	0.66	–0.03	0.10	0.20
35	0.75	–0.03	0.10	0.20
40	0.69	–0.03	0.13	0.23
45	0.89	–0.03	0.13	0.30
50	1.05	0.00	0.20	0.36
55	1.54	0.07	0.23	0.49
60	1.71	0.16	0.36	0.72
65	2.13	0.16	0.33	0.66
Performance standards[a]				
	1.00	<0.20	—	<0.80
	Met, angle <50	Met	—	Met

[a]Performance standard check values are from U.S. Army Corps of Engineers (2013, table 3–1).

Patch Tests

Patch tests are a series of dynamic calibration tests that are used to check for subtle variations in the orientation and timing of the MBES with respect to the INS and real-world coordinates. The patch tests are used to determine timing offsets caused by latency between the MBES and the INS, and angular offsets to roll, pitch, and yaw caused by the alignment of the transducer head (fig. 4). These offsets have been observed to be essentially constant for a given survey, barring an event that causes the mount to change such as striking a floating or submerged object (Huizinga, 2010, 2011, 2012, 2014, 2015, 2016).



EXPLANATION

Actual bottom — Measured bottom

Δt Timing offset for latency between the multibeam echosounder and Global Navigation Satellite System components of the inertial navigation system

α Angular offset for roll of the transducer head along the longitudinal axis of the boat

β Angular offset for pitch of the transducer head along the lateral axis of the boat

δ Angular offset for yaw of the transducer head about the vertical axis

Figure 4. Generalized effects on data from a multibeam echosounder. *A*, timing offset for latency. *B*, angular offset for roll. *C*, angular offset for pitch. *D*, angular offset for yaw.

The offsets determined in the patch test are applied when processing the data collected during a given survey.

Patch tests were completed before the 2016 surveys at the Lake of the Ozarks near Osage Beach, Mo. (fig. 1, index map), and again on the last day of surveying, while at site 27 (structure A3047 on U.S. Highway 67; fig. 1) over the Missouri River near St. Louis (table 3). Although the MBES had several minor strikes of floating debris at various times during the 2016 surveys, there were no apparent changes to the roll, pitch, or yaw angles from the beginning to the end of the surveys (table 3).

For this study, there was no measured timing offset (table 3; Δt=0, fig. 4), which is consistent with latency test results for this boat and similar equipment configuration used in other surveys (Huizinga, 2010, 2011, 2012, 2013, 2014, 2015, 2016; Huizinga and others, 2010). The measured angular offset for pitch and yaw for all head-tilt configurations remained constant at –1.00 degree and 1.00 degree, respectively, for both patch tests (table 3). The measured angular offset for roll also remained constant for both patch tests for the various head tilt configurations (table 3) with –2.35 degrees for no tilt, –32.45 degrees for 30 degrees to starboard tilt, and 27.75 degrees for 30 degrees to port tilt. The measured offset angles for roll, pitch, and yaw are somewhat different from previous surveys with this equipment (Huizinga, 2016, table 3), and likely is the result of adjustments made to the mount between mobilization for the 2015 and 2016 surveys. It was noted in Huizinga (2010) that a sensitivity analysis of the four offsets implied that the ultimate position of surveyed points in three-dimensional space was least sensitive to the angular offset for yaw, whereas it was most sensitive to the angular offset for roll.

The bathymetric data were processed to apply the offsets determined from the patch tests, and to remove data spikes and other spurious points in the multibeam swaths through the use of automatic filters and manual editing. The bathymetric data were then projected to a three-dimensional grid at a resolution of 1.64 ft using the Combined Uncertainty Bathymetric Estimator (CUBE) method (Calder and Mayer, 2003), as implemented in the MB–MAX processing package of the HYPACK®/HYSWEEP® software (HYPACK, Inc., 2015) and used to generate a gridded raster surface of the channel bed near each bridge (hereinafter referred to as a "bathymetric surface") using ArcGIS. The bathymetric surface for each site from the 2016 survey was compared to similar bathymetric

Table 3. Patch test results at the Lake of the Ozarks near Osage Beach, Missouri, on March 29, 2016, and on the Missouri River in St. Louis, Missouri, on May 27, 2016.

[sec, second; deg, degree]

Date of test	Timing offset (sec)	Angular offset for roll (deg)	Angular offset for pitch (deg)	Angular offset for yaw (deg)	Head tilt
03/29/16	0	–2.35	–1.00	1.00	None.
05/27/16	0	–2.35	–1.00	1.00	None.
03/29/16	0	–32.45	–1.00	1.00	30 degrees starboard.
05/27/16	0	–32.45	–1.00	1.00	30 degrees starboard.
03/29/16	0	27.75	–1.00	1.00	30 degrees port.
05/27/16	0	27.75	–1.00	1.00	30 degrees port.

surfaces created from previous surveys at a bridge by taking the difference between the 2016 raster surface and the previous survey raster surface. Statistics of the elevations for each bathymetric surface were determined, as were statistics of the differences between the surfaces. Sediment volumes for cut (scour) and fill (deposition) between the 2016 survey and previous surveys in 2009, 2010 and 2011 also were determined from differences in the raster surfaces using ArcGIS.

Uncertainty Estimation

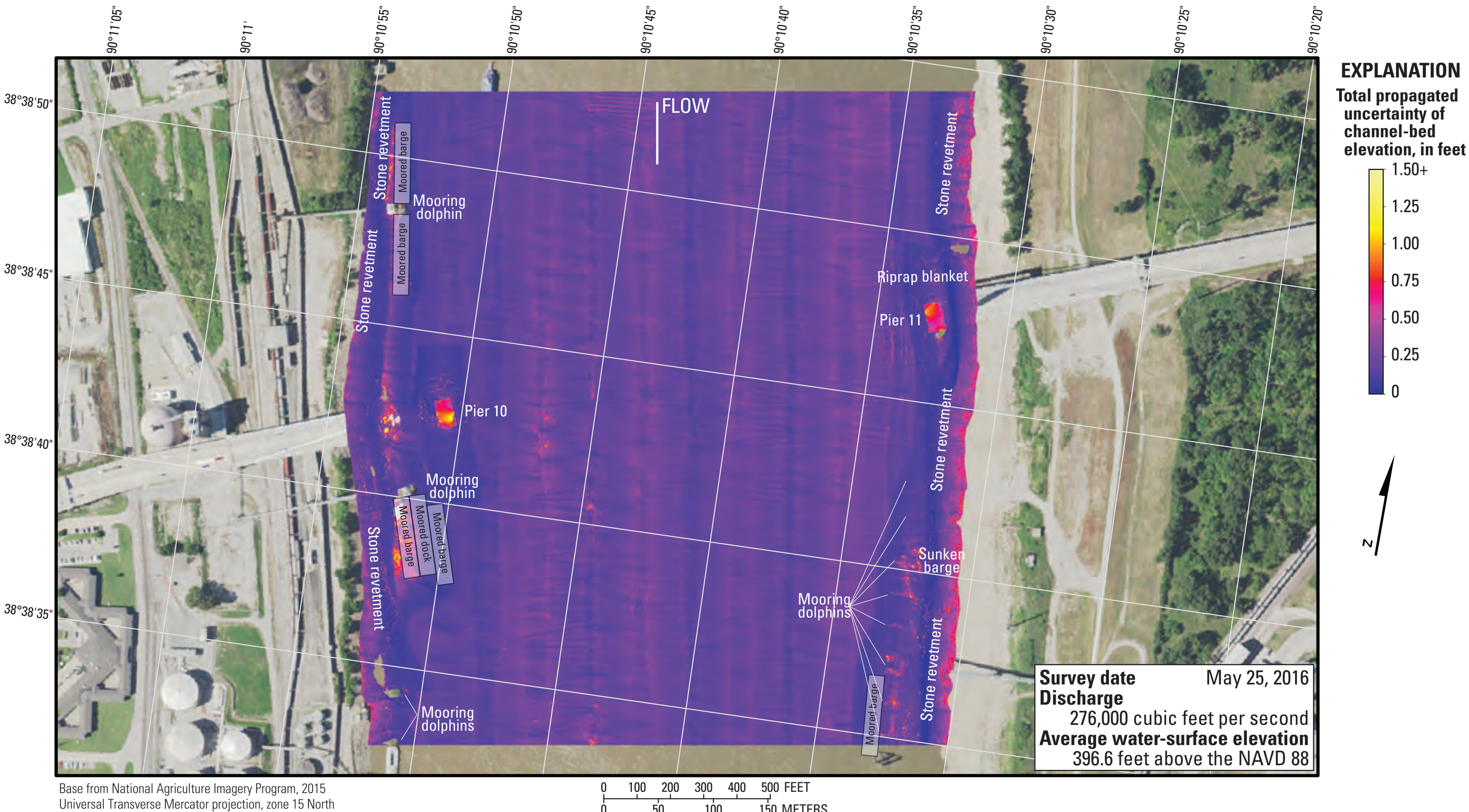
Similar to the previous studies of bathymetry in Missouri (Huizinga, 2010, 2011, 2012, 2013, 2014, 2015, 2016), uncertainty in the surveys was estimated by computing the total propagated uncertainty (TPU) for each survey-grid cell in the bathymetric surface of each survey area, using the CUBE method (Calder and Mayer, 2003) as implemented in the MBMAX processing package of the HYPACK®/HYSWEEP® software (HYPACK, Inc., 2015). The CUBE method allows all random system component uncertainties and resolution effects to be combined and propagated through the data processing steps, which provides a robust estimate of the spatial distribution of possible uncertainty within the survey area (Czuba and others, 2011); thus, the TPU of a point is a measure of the accuracy to be expected for such a point when all relevant error sources are taken into account (Czuba and others, 2011). Statistics of TPU for each of the survey areas are shown in table 4, and an example of the spatial distribution of TPU typically observed in the survey data is shown in figure 5 for the bathymetric data at structure A6500 on Interstate 70 over the Mississippi River.

The largest TPU in this group of surveys was about 2.53 ft (table 4); however, as noted in previous studies, TPU values of this magnitude typically happened near high-relief features, such as the front or side of a pier footing (fig. 5). Most of the TPU values (more than 97 percent) were less than 0.50 ft (table 4), which is within the specifications for a “Special Order” survey, the most-stringent survey standard of the International Hydrographic Organization (IHO; International Hydrographic Organization, 2008). The TPU values were larger near moderate-relief features (banks, spur dikes, rock riprap and outcrops, and scour holes near piers; fig. 5). Occasionally, the TPU values also were larger (1.00 ft or greater) in the outermost beam extents of the multibeam swath in the

Table 4. Total propagated uncertainty results for bathymetric data at a 1.64-foot grid spacing from surveys on the Missouri and Mississippi Rivers near St. Louis, Missouri, May 23–27, 2016.

[MoDOT, Missouri Department of Transportation; ft, foot]

Site number (fig. 1)	MoDOT structure number	Maximum value of uncertainty (ft)	Mean value of uncertainty (ft)	Median value of uncertainty (ft)	Standard deviation of uncertainty (ft)	Percentage of bathymetry points with uncertainty value less than			
						2.00 ft	1.00 ft	0.50 ft	0.25 ft
23	A7577/A4017	1.38	0.17	0.13	0.12	100.0	99.8	97.2	90.9
24	A5585 E & W	1.71	0.15	0.13	0.11	100.0	99.9	97.9	92.3
25	A3292/L0561	1.54	0.16	0.13	0.13	100.0	99.7	97.0	87.1
26	A4557 E & W	1.44	0.14	0.13	0.09	100.0	99.9	98.7	93.1
27	A3047	1.38	0.15	0.13	0.11	100.0	99.9	97.9	92.8
33	A6500	2.00	0.21	0.20	0.08	100.0	99.9	99.1	78.7
34	A1500	2.53	0.20	0.20	0.09	100.0	99.9	98.5	89.0
35	A4936/A1850	1.71	0.19	0.20	0.08	100.0	99.9	99.0	89.6



Base from National Agriculture Imagery Program, 2015
Universal Transverse Mercator projection, zone 15 North
Horizontal coordinate information referenced to the North American Datum of 1983 (NAD 83)
Vertical coordinate information referenced to the North American Vertical Datum of 1988 (NAVD 88)

Figure 5. Total propagated uncertainty of bathymetric data from the Mississippi River channel near structure A6500 on Interstate 70 in St. Louis, Missouri.

overlap with an adjacent swath, particularly when the MBES head was tilted for the survey lines along the banks or near the piers (fig. 5). Overlapping adjacent swaths in the channel thalweg (the line of maximum depth in the channel) also can display larger TPU values because substantial bed movement can happen between survey passes (fig. 5). More than three-quarters (78 percent or more) of the channel bed at the sites had TPU values of 0.25 ft or less (table 4). The tops of bridge substructural elements (pier footings and seal courses) typically had TPU values of 0.25 ft or less.

The survey at structure A6500 on Interstate 70 had the highest mean value of TPU, as well as generally the lowest percentage of bathymetry points that were less than the various TPU value cutoffs (table 4). There were a few impediments to surveying at this site in the form of mooring dolphins and moored barges along both banks, but otherwise the survey was obtained with relatively smooth longitudinal swathes (fig. 5), which was the case at nearly all the sites surveyed in this study. The primary anomaly at this site was near a series of moored barges along the right bank ("left" and "right" refer to directions that would be reported by an observer facing downstream), where objects on the channel bed and limited coverage resulted in substantial TPU values (fig. 5). Substantial TPU values also were observed near the piers because of the vertical sides of the footings and seal courses (fig. 5). Generally, the magnitude and distribution of TPU values observed at this site are representative of those observed at all the other surveyed sites.

Results of Bathymetric and Velocimetric Surveys

The site-specific results for each bridge are discussed in the following sections, starting with the upstream-most bridge site on the Missouri River and progressing downstream along the Mississippi River. The site-specific results are followed by a discussion of general findings that are not specific to a particular site. The range of bed elevations described as "the channel-bed elevations" for each survey was based on statistical analysis of the gridded raster surface of the bathymetry data at each site, and covers the percentile range from 5 to 95 percent of the data. Because the surveys generally were limited to the active channel from bank to bank excluding overbank areas, this percentile range generally covered the channel bed but excluded the banks and localized high or low spots, such as spur dikes or scour holes near piers. All elevation data were referenced to the North American Vertical Datum of 1988 (NAVD 88).

For consistency with earlier studies, dune sizes are described in general terms for each of the bridge sites using the categories set by Huizinga (2012) for the discussion of bathymetry during the 2011 flood. In this report, small dunes and ripples are those that are less than 5 ft high from crest to trough, medium dunes are those that are 5 to 10 ft high, large dunes are those that are 10 to 15 ft high, and very large dunes are those that are 15 ft or more in height.

Previous bathymetric surveys have happened at all the bridge sites in this study (Huizinga, 2010, 2012; Huizinga and others, 2010); furthermore, several of the sites had a Level II bridge scour assessment (Lagasse and others, 1991; Huizinga and Rydlund, 2004). A map showing the difference in channel-bed elevation for the area common to each surveys is included for each site, and data from previous surveys are included in the cross-section plot for that bridge. The difference maps were created by taking the difference between the 2016 raster surface and a previous survey raster surface at a given bridge, and summary statistics (maximum, minimum, and mean) of the difference rasters were determined. The surveys are broadly compared based on their timing and the discharge at the time of the survey. If a site was subject to a Level II assessment, the cross section of the channel on the downstream side of the bridge obtained during the Level II assessment is included on the cross-section plot for that bridge.

Although the configuration of the channel bed and the underlying sediment transport conditions at a given site are associated with an instantaneous discharge in the discussions that follow, a given bathymetric surface actually is a reflection of more than those instantaneous transport conditions. A wide variety of factors affect the channel-bed configuration of a reach for a given discharge (Gilbert and Murphy, 1914), including flow velocities and velocity distribution, the size and timing of previous flood rises, whether or not the stage currently is rising or falling, and other local hydraulic conditions; furthermore, the channel-bed configuration at a site is affected by upstream and local sediment conditions and contributions, as well as water temperature and other seasonal variations. Because of the myriad number and interactions of factors affecting sediment transport conditions and the resultant bed configuration, it would be simplistic to assume that the configuration and size of bed forms observed during the current (2016) surveys near St. Louis are dependent only upon the instantaneous discharge at a given site. Although it is beyond the scope of the current (2016) study to examine all the antecedent conditions that created the observed channel-bed configuration, the comparisons with previous surveys under different flow conditions nevertheless contribute to understanding the many complexities of sediment transport.

As in recent previous studies (Huizinga, 2012, 2013, 2014, 2015, 2016), when discussing the vertically averaged velocity values obtained during the surveys in the sections that follow, neighboring vectors having random variations in direction and magnitude were taken as an indication of nonuniform flow in the section resulting from shear and wake vortices. Conversely, neighboring vectors having gradual and systematic variations were taken as an indication of uniform flow in the section. The velocity data for each section are an average of two velocity transects, spatially averaged to the section line using algorithms in the Velocity Mapping Toolbox (Parsons and others, 2013).

Shaded TIN images of the channel and side of pier were prepared for each surveyed pier. These visualizations are shown in appendix figures 1–1 to 1–9.

Structures A7577 and A4017 on U.S. Highway 40

Structures A7577 and A4017 (site 23) are dual bridges on U.S. Highway 40, crossing the Missouri River at river mile (RM) 43.9, on the northwestern side of the St. Louis metropolitan area between Chesterfield and Weldon Spring, Mo. (fig. 1). The site was surveyed on May 23, 2016, and the average water-surface elevation near the bridge, determined by the RTK GNSS tide solution, was 446.0 ft (table 5). Discharge on the Missouri River was about 117,000 ft^3/s during the survey (table 5).

The survey area was about 1,840 ft long and about 1,480 ft wide, extending across the active channel from bank to bank (fig. 6). The upstream end of the survey area was about 620 ft upstream from the centerline of structures A7577 and A4017 (fig. 6). The channel-bed elevations ranged from about 413 to 435 ft for most of the surveyed area (5th to 95th percentile range of the bathymetric data; table 5; fig. 7), except near the main channel piers of structures A7577 and A4017 and near the ends of or downstream from various spur dikes (fig. 6). The thalweg was not well defined in the upstream channel, but seemed to develop downstream from the bridges, and was about 8 ft deeper than the channel bed in the middle of the channel (fig. 6). A series of small to medium dunes was present in the middle of the channel, and numerous other small dunes and ripples were present throughout the rest of the channel (fig. 6). As in previous surveys (Huizinga, 2011, 2012), a rock outcrop and a longitudinal spur dike were present on the left (north) bank downstream from the bridges, and several other spur dikes were present on both banks (fig. 6). A construction causeway had been built into the channel from the left bank upstream from structure A7577 and the spur dike on the left bank under structure A4017 (fig. 6). Remnants of piers from old downstream structure J1000 are evident downstream from the spur dike on the left bank and downstream from pier 5 of downstream structure A4017 (fig. 6).

Near the piers near the left bank (structure A7577 bents 6 and 7, and structure A4017 pier 4, fig. 6), a localized deep scour hole near the end of the construction causeway upstream from the spur dike had an approximate minimum channel-bed elevation of about 410 ft (table 6); however, bent 6 of structure A7577 and pier 4 of structure A4017 essentially were embedded in the rock of the construction causeway and spur dike on the left bank (fig. 6), which will limit or prevent scour near these piers. Near bent 7 of upstream structure A7577, a local scour hole had an approximate minimum channel-bed elevation of about 406 ft (table 6), about 5 ft above the approximate minimum channel-bed elevation of 401 ft (table 5), and about

Table 5. Bridge and survey information, and selected channel-bed elevations from surveys on the Missouri and Mississippi Rivers near St. Louis, Missouri, May 23–27, 2016.

[MoDOT, Missouri Department of Transportation; ADCP, acoustic Doppler current profiler; ft^3/s, cubic foot per second; ft, foot; US, U.S. highway; E, east-bound; W, west-bound; MO, State highway; IS, Interstate highway; all elevations are in feet above the North American Vertical Datum of 1988]

Site number (fig. 1)	MoDOT structure number	Survey date	Route	River mile[a]	Discharge from ADCP measurements[b] (ft^3/s)	Average water-surface elevation near the bridge (ft)	Average channel-bed elevation[c] (ft)	Approximate channel-bed elevation of the indicated percentile of the bathymetric data		Approximate minimum channel-bed elevation[d] (ft)
								5th percentile (ft)	95th percentile (ft)	
23	A7577/A4017	05/23/16	US 40	43.9	117,000	446.0	423.1	412.7	434.7	401
24	A5585 E & W	05/24/16	MO 364	32.7	110,000	434.1	414.4	406.0	424.1	399
25	A3292/L0561	05/24/16	IS 70	29.6	116,000	431.8	412.2	403.6	422.8	389
26	A4557 E & W	05/24/16	MO 370	27.0	114,000	429.9	408.0	399.0	416.8	388
27	A3047	05/27/16	US 67	8.1	131,000	413.7	392.1	381.3	403.0	374
33	A6500	05/25/16	IS 70	181.2	276,000	396.6	362.2	353.5	382.5	334
34	A1500	05/25/16	IS 55	179.2	279,000	395.7	360.5	350.0	382.0	340
35	A4936/A1850	05/26/16	IS 255	168.8	290,000	390.5	359.7	350.1	375.3	322

[a]For sites 23–27, river mile is the distance upstream on the Lower Missouri River, starting at the confluence with the Mississippi River at St. Louis, Mo. (fig. 1), at river mile 195.2 of the Upper Mississippi River. For sites 33–35, river mile is the distance upstream on the Upper Mississippi River, starting at the confluence with the Ohio River at Cairo, Ill. (fig. 1), at river mile 953.5 of the Lower Mississippi River.

[b]The average discharge obtained while making the various velocity transects. The reported value is the discharges computed using Global Navigation Satellite System (GNSS) essential fix GGA data string as the reference, as described in the "Surveying Methods" section of the text.

[c]The statistical average of the gridded raster surface of channel-bed elevations.

[d]The minimum channel-bed elevation of the gridded raster surface, not necessarily in any scour holes near the bridge.

Structures A7577 and A4017 on U.S. Highway 40.

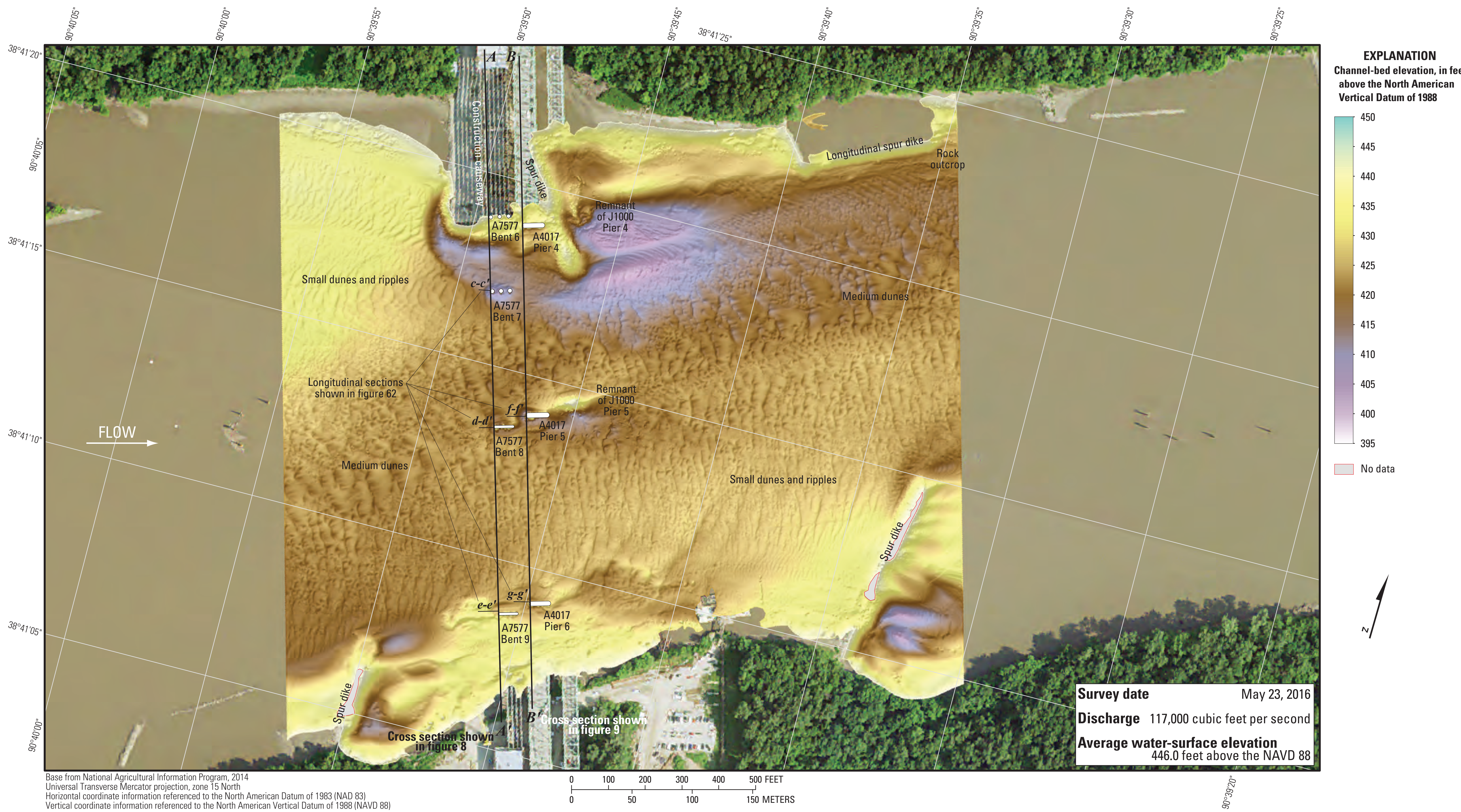


Figure 6. Bathymetric survey of the Missouri River channel near structures A7577 and A4017 on U.S. Highway 40 near St. Louis, Missouri.

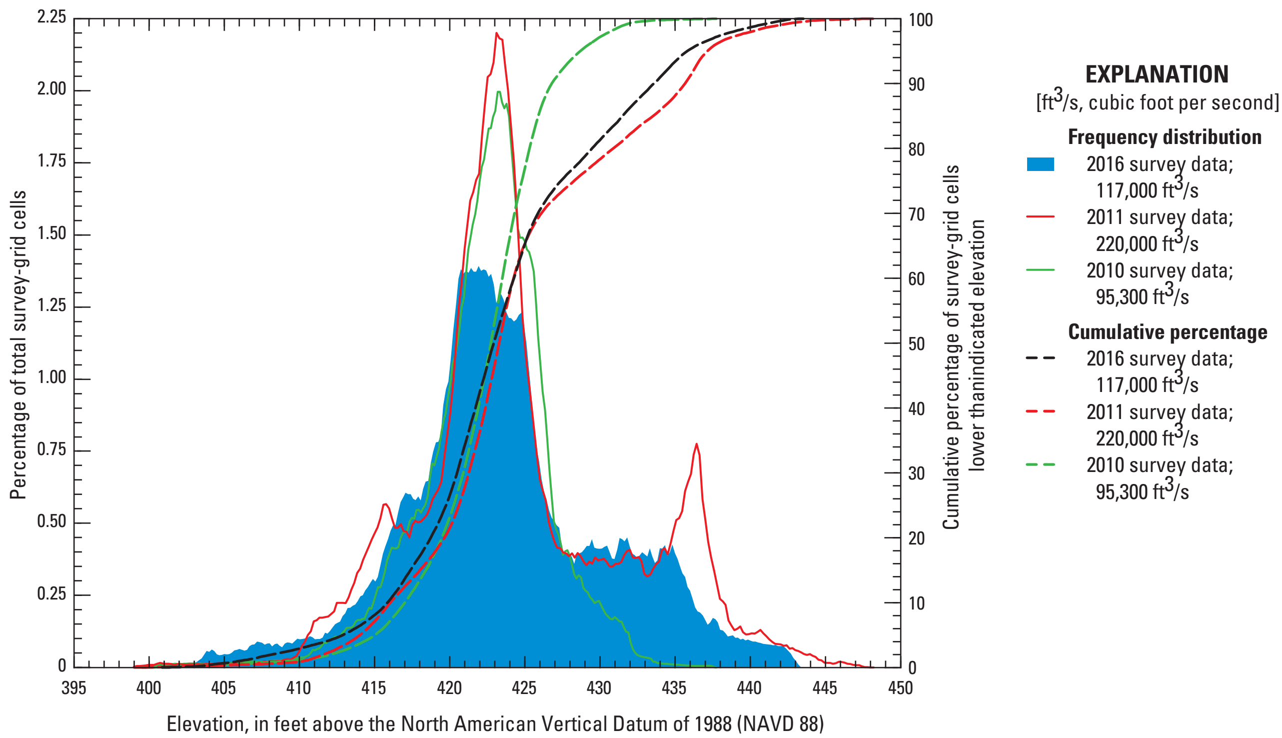


Figure 7. Frequency distribution of bed elevations for bathymetric survey-grid cells on the Missouri River near structures A7577 and A4017 on U.S. Highway 40 near St. Louis, Missouri, on May 23, 2016, compared to previous surveys.

9 ft below the average channel bed immediately upstream from the bent (the "Depth of scour hole from upstream channel bed," table 6; fig. 6). A local scour hole near pier 5 of downstream structure A4017 had a minimum elevation of 412 ft, about 11 ft below the average channel bed immediately upstream from the pier, and slightly deeper than the approximate minimum elevation of the local scour hole near bent 8 of upstream structure A7577 of 415 ft (fig. 6; table 6).

Information from bridge plans indicate that all the bents of structure A7577 are shafts drilled 15 to 16 ft into bedrock, with about 20 ft of bed material between the bottom of the scour hole and bedrock at bent 7 (fig. 8; table 6), which increases substantially to the right (south) because of the sloping bedrock in the area (fig. 8; table 6). Information from bridge plans indicate that pier 4 of structure 4017 is a footing founded on bedrock, and about 15 ft of bed material was present between the bottom of the scour hole and bedrock (fig. 9; table 6). Piers 5 and 6 of structure A4017 are founded on shafts drilled 13 to 26 ft into bedrock, and more than 44 ft of bed material was present between the bottom of the scour hole and bedrock (fig. 9; table 6) because of the sloping bedrock in the area (fig. 9; table 6).

The difference between the survey on May 23, 2016, and the previous flood survey on July 29, 2011, does not indicate substantial bed variation from 2011 to 2016, with the exception of areas near the construction causeway on the left bank and around the various spur dikes (fig. 10). There was an area of substantial deposition near the location of pier 5 of old structure J1000, where a scour hole present in the 2011 survey (Huizinga, 2012) has subsequently been filled (fig. 10). The mean difference between the bathymetric surfaces (the statistical mean value of the gridded raster surface [fig. 10] created from the difference between the 2016 and 2011 [previous] survey gridded raster bathymetric surfaces) was –0.27 ft (table 7), indicating overall minor channel degradation between the 2011 and 2016 surveys. The net volume of cut in the reach from 2011 to 2016 was about 144,300 cubic yards (yd^3), and the net volume of fill was about 117,700 yd^3, resulting in a net loss of about 26,700 yd^3 of sediment between 2011 and 2016. The cross sections from the two surveys along the upstream face of the upstream structure A7577 bridge are not substantially different from one another between bents 7 and 9 except near the new bents, but the scouring effect of the construction causeway is clearly evident between bents 6 and 7 (fig. 8). The frequency distribution of bed elevations also was not substantially different in shape in 2016 than in 2011, except without the higher percentage of survey-grid cells with elevations between 420 and 426 ft evident in the 2011 and 2010 surveys, and without the spike of grid cells with elevations around 436 ft evident in 2011 (fig. 7). A large mound of rock near bent 9 of upstream structure A7577 (fig. 8) also had been removed, which resulted in an area of substantial scour indicated near that bent and deposition around pier 6 of downstream structure A4017 (fig. 10). The rock outcrop on the downstream left (north) bank showed no signs of substantial change except for minor deposition along the toe of the

Table 6. Results near piers and bents from surveys on the Missouri River near St. Louis, Missouri, May 23–27, 2016.

[MoDOT, Missouri Department of Transportation; ft, foot; —, not known/applicable; all elevations are in feet above the North American Vertical Datum of 1988]

Site number (fig. 1)	MoDOT structure number	MoDOT pier/bent number	Foundation information				Approximate minimum channel-bed elevation in scour hole near pier/bent[a] (ft)	Approximate elevation of scour hole at upstream pier/bent face (ft)	Approximate elevation of bedrock near pier/bent (ft)	Approximate distance between bottom of scour hole and bedrock (ft)	Depth of scour hole from upstream channel bed (ft)	Approximate frontal slope of scour hole (ft/ft)
			Type	Width (ft)	Penetration into bedrock (ft)	Bottom of seal course elevation (ft)						
23	A7577	6	Drilled shaft	10	16	—	410	[b]443	404	[b]6	([b])	([b])
		7	Drilled shaft	11.5	15	—	406	407	386	20	9	1.43
		8	Drilled shaft	8	15	396.00	415	417	369	46	5	3.03
		9	Drilled shaft	8	16	406.00	421	422	355	66	9	2.82
	A4017	4	Footing	32	1	—	420	[b]429	405	15	([b])	([b])
		5	Drilled shaft	24	26	383.00	412	412	368	44	11	1.79
		6	Drilled shaft	28	13	390.00	420	422	360	60	2	[c]5.95
24	A5585 Eastbound	5	Drilled shaft	32.9	11	371.62	406	406	372	34	8	1.94
		6	Drilled shaft	33.5	11	371.62	410	410	358	52	6	2.90
		7	Drilled shaft	33.5	11	371.62	420	420	351	69	3	([d])
	A5585 Westbound	5	Drilled shaft	32.9	11	371.62	407	407	372	35	6	1.85
		6	Drilled shaft	33.5	11	371.62	407	407	358	49	4	[c]6.25
		7	Drilled shaft	33.5	11	371.62	415	415	351	64	3	[c]4.65
25	A3292	15	Drilled shaft	29.5	16	378.00	407	408	350	57	13	1.67
		16	Drilled shaft	29.5	17	378.00	399	399	342	57	12	1.06
	L0561	16	Caisson	24	1	—	409	410	351	58	10	2.03
		17	Caisson	24	3	—	389	389	343	46	18	2.20
26	A4557 Eastbound	2C	Drilled shaft	24	15	386.00	403	403	358	45	4	2.76
		3C	Drilled shaft	24	15	388.00	402	402	353	49	6	2.05
		4C	Drilled shaft	24	15	394.00	411	411	345	66	3	([d])
	A4557 Westbound	2C	Drilled shaft	24	15	386.00	401	401	358	43	6	2.96
		3C	Drilled shaft	24	15	388.00	402	402	353	49	[c]6	([c])
		4C	Drilled shaft	24	15	394.00	403	421	345	58	([b])	([b])
27	A3047	10	Drilled shaft	26	13	346.50	379	388	303	76	([b])	([b])
		11	Drilled shaft	26	15	346.50	375	375	314	61	12	1.22
		12	Drilled shaft	26	26	359.00	392	392	336	56	6	1.68

[a]The point of lowest elevation in the scour hole near the bridge pier/bent, not necessarily at the upstream face.

[b]Scour hole at this pier/bent is substantially affected by adjacent spur dike or construction dike.

[c]Scour hole at this pier/bent is substantially affected by upstream pier.

[d]Poorly defined scour hole at this pier/bent.

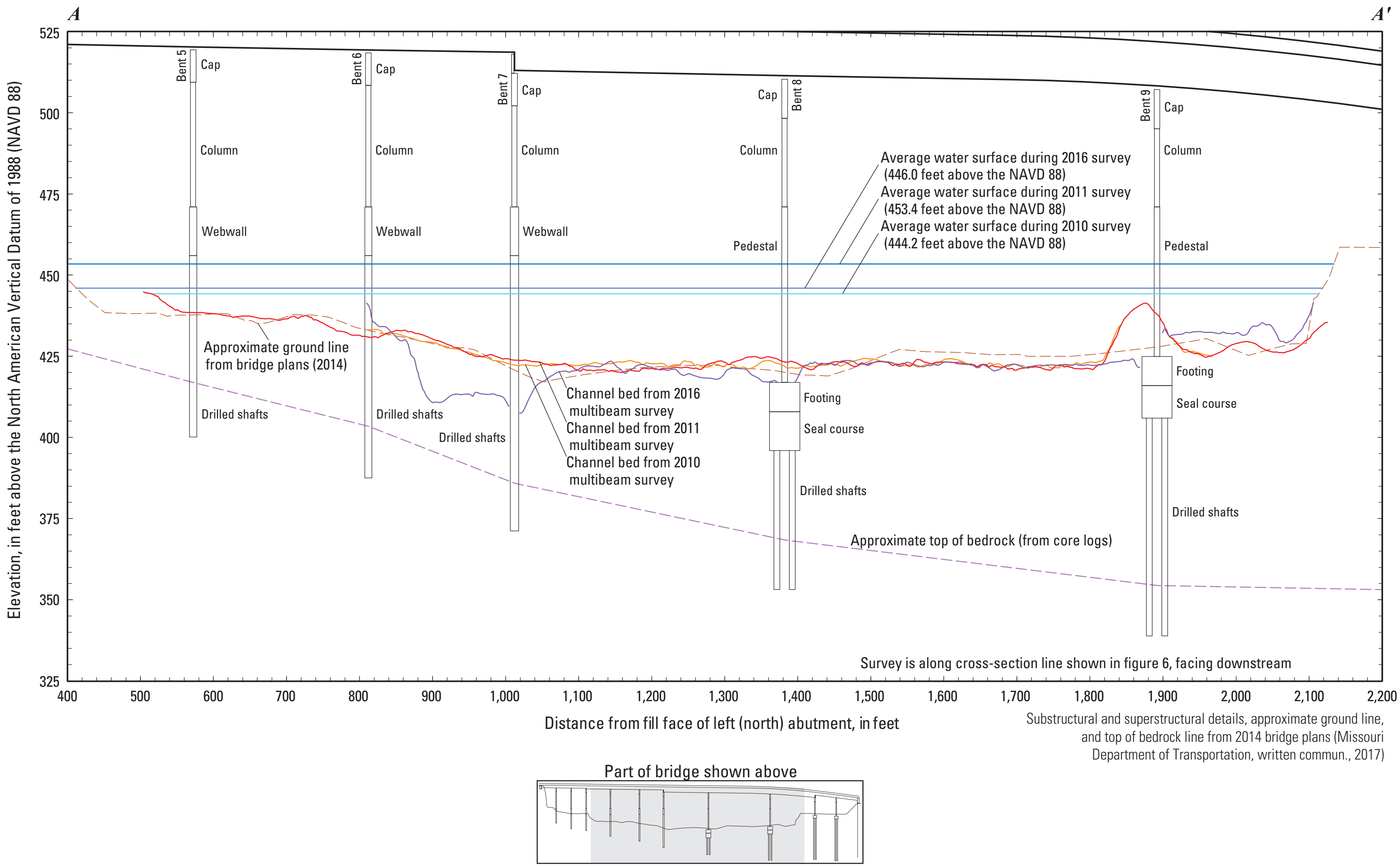


Figure 8. Key features, substructural and superstructural details, and surveyed channel bed of structure A7577 on U.S. Highway 40 crossing the Missouri River near St. Louis, Missouri.

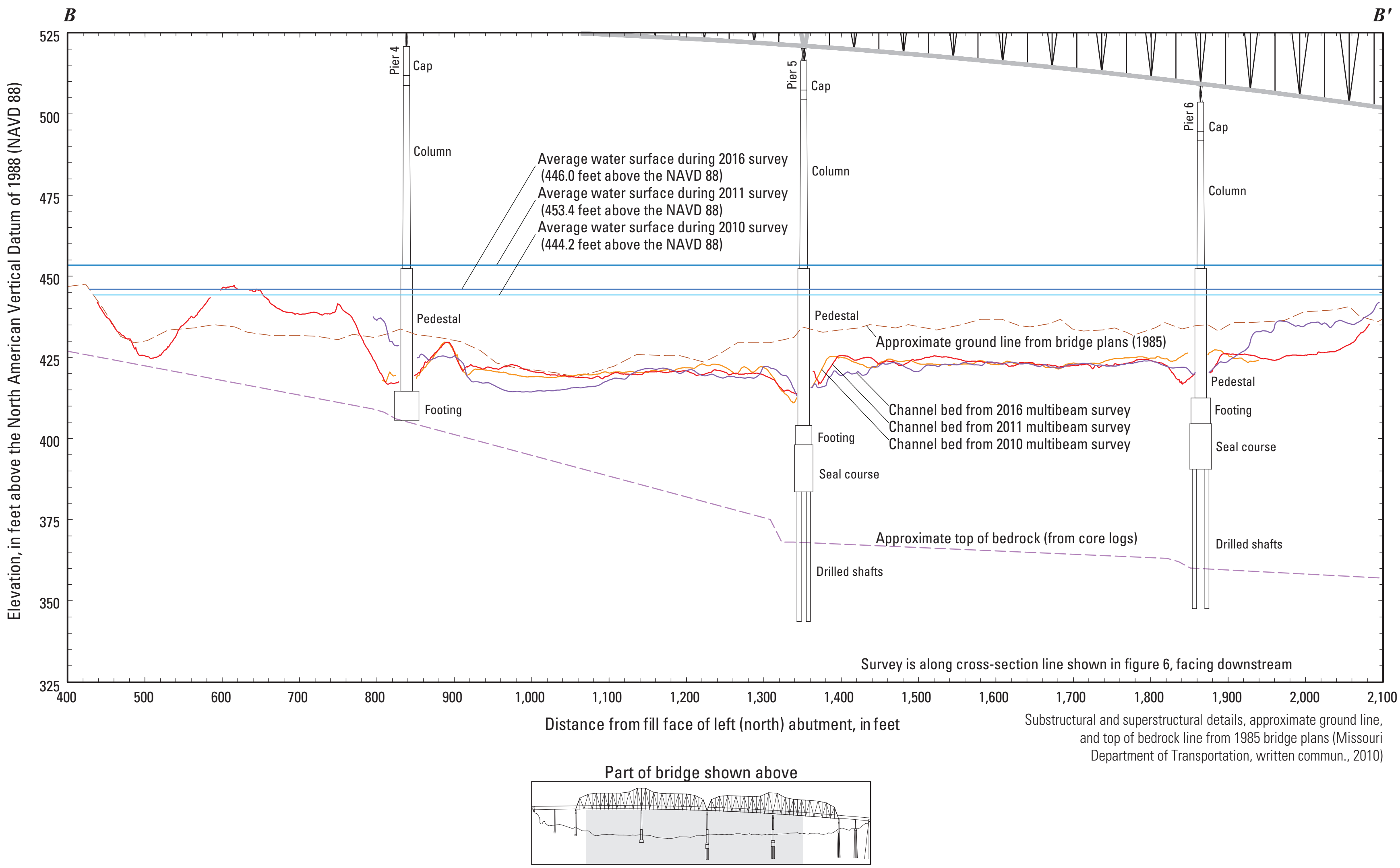


Figure 9. Key features, substructural and superstructural details, and surveyed channel bed of structure A4017 on U.S. Highway 40 crossing the Missouri River near St. Louis, Missouri.

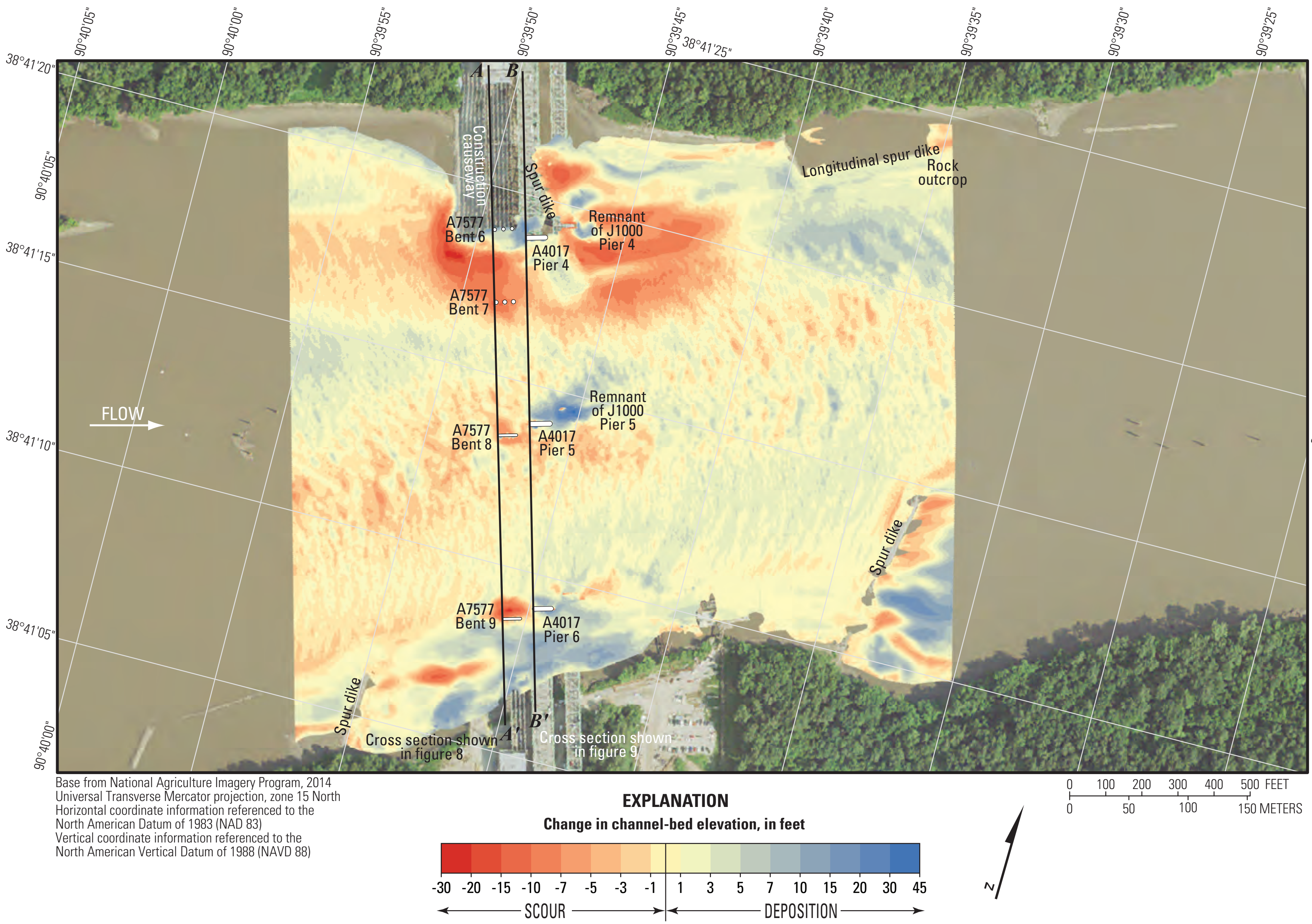


Figure 10. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structures A7577 and A4017 on U.S. Highway 40 near St. Louis, Missouri, on May 23, 2016, and July 29, 2011.

Table 7. Summary information and bathymetric surface difference statistics from surveys on the Missouri and Mississippi Rivers near St. Louis, Missouri, from May 23–27, 2016, and previous surveys.

[MoDOT, Missouri Department of Transportation; ft^3/s, cubic foot per second; ft^2, square foot; ft, foot; A, Huizinga (2011); B, Huizinga (2012); C, Huizinga and others (2010); all elevations are in feet above the North American Vertical Datum of 1988]

Site number (fig. 1)	MoDOT structure number	Previous survey					Difference between 2016 survey and previous survey			Statistics of differences between 2016 and previous survey surfaces				Maximum-difference near upstream pier/bent face(s)[b,c] (ft)
		Source of data	Date	Discharge (ft^3/s)	Surveyed area ($x10^6$ ft^2)	Average water-surface elevation (ft)	Discharge (ft^3/s)	Surveyed area ($x10^6$ ft^2)	Average water-surface elevation (ft)	Minimum[a,b] (ft)	Maximum[a,b] (ft)	Mean[b] (ft)	Standard deviation (ft)	
23	A7577/A4017	A	10/18/10	95,300	[d]4.167	444.2	21,700	–1.460	1.8	–21.7	34.2	–1.41	3.20	[e]–15.7
		B	07/29/11	220,000	2.872	453.4	–103,000	–0.165	–7.4	–23.1	33.7	–0.27	3.97	[e]–16.6
24	A5585 E & W	A	10/21/10	91,600	1.550	432.0	18,400	0.492	2.1	–14.1	12.1	–0.24	2.17	5.8
		B	08/01/11	224,000	2.002	443.2	–114,000	0.039	–9.1	–15.4	17.3	0.16	2.87	13.1
25	A3292/L0561	A	10/21/10	91,600	1.847	430.0	24,400	0.205	1.8	–21.6	33.5	0.86	2.26	12.6
		B	08/02/11	225,000	1.981	440.4	–109,000	0.071	–8.6	–27.4	38.3	2.23	2.99	19.3
26	A4557 E & W	A	10/22/10	90,000	1.899	428.4	24,000	0.143	1.5	–26.6	24.6	–0.20	1.71	–4.3
		B	08/02/11	225,000	2.037	438.2	–111,000	0.005	–8.3	–26.5	27.2	–0.07	1.61	–3.4
27	A3047	A	10/25/10	87,400	1.680	410.2	43,600	0.365	3.5	–19.9	16.3	–1.77	2.36	–7.6
		B	08/03/11	225,000	2.216	421.8	–94,000	–0.171	–8.1	–22.7	22.3	0.77	2.05	–8.2
33	A6500	C	07/07/09	295,000	[d]5.981	398.2	–19,000	–2.409	–1.6	–29.7	40.1	–1.36	4.98	[e]–16.8
34	A1500	A	10/20/10	277,000	[d]6.992	396.5	2,000	–4.293	–0.8	–22.0	29.4	–0.38	3.41	–3.7
35	A4936/A1850	A, C	10/02–03/08	215,000	[d]7.963	383.8	75,000	–4.701	6.7	–21.2	31.5	0.53	2.73	12.1
		A, C	05/12–13/09	424,000	[d]9.069	403.7	–134,000	–5.807	–13.2	–35.8	32.1	–0.17	2.88	8.5
		A, C	07/08/09	271,000	[d]7.937	390.3	19,000	–4.675	0.2	–17.6	23.6	0.51	2.82	12.6
		A	10/19/10	288,000	[d]8.111	391.6	2,000	–4.849	–1.1	–24.4	32.4	0.77	2.20	12.0

[a]The maximum or minimum value of change likely is near a vertical pier/bent face and affected by minor position variances.

[b]A positive value represents deposition, a negative value represents scour.

[c]The maximum difference near the upstream pier/bent face was taken near the location of the “approximate elevation of scour hole at upstream pier/bent face” in tables 6 and 8.

[d]The surveyed reach was substantially longer than in the 2016 survey.

[e]At the location of a new pier/bent compared to previous survey.

longitudinal spur dike (fig. 10). Although rock ultimately is an erodible material, its rate of erosion is substantially slower than that of sand and silt (Richardson and Davis, 2001).

The difference between the survey on May 23, 2016, and the previous nonflood survey on October 18, 2010, does not indicate substantial bed variation from 2010 to 2016, again with the exception of near the construction causeway on the left bank and downstream from the spur dike on the left bank (fig. 11). There was an area of substantial deposition near the location of pier 5 of old structure J1000, where a scour hole present in the 2010 survey (Huizinga, 2011) has subsequently been filled (fig. 11). The mean difference between the bathymetric surfaces was –1.41 ft (table 7), indicating moderate channel degradation between the 2010 and 2016 surveys for the area common to both surveys. The net volume of cut in the reach from 2010 to 2016 was about 132,100 yd^3, and the net volume of fill was about 30,800 yd^3, resulting in a net loss of about 101,300 yd^3 of sediment between 2010 and 2016. The cross sections from the two surveys along the upstream face of the upstream structure A7577 bridge are not substantially different from one another between bents 7 and 9 except near the new bents, but the scouring effect of the construction causeway again is clearly evident between bents 6 and 7 (fig. 8). The frequency distribution of bed elevations also was similar in shape in 2016 compared to 2010; however, a lower percentage of grid cells had elevations between 420 and 426 ft, and a higher percentage of survey-grid cells had elevations between 429 and 443 ft (fig. 7). Again, the large mound of rock near bent 9 of upstream structure A7577 (fig. 8) also had been removed, with a resultant area of substantial scour indicated near that bent (fig. 11).

The vertically averaged velocity vectors indicate mostly uniform flow throughout the reach (fig. 12). A maximum velocity of about 8 feet per second (ft/s) was present in the upstream channel thalweg and a minimum of 1 ft/s with flow reversal downstream from the various spur dikes in the reach (fig. 12). The flow constriction resulting from the presence of the construction causeway is clearly evident in the vectors upstream from the bridges (fig. 12). A minor decrease in velocity was observed downstream from bent 8 of upstream structure A7577 and pier 5 of downstream structure A4017, likely exacerbated by the bent and pier being skewed to flow (fig. 12). Minor turbulence was present in all the sections (fig. 12).

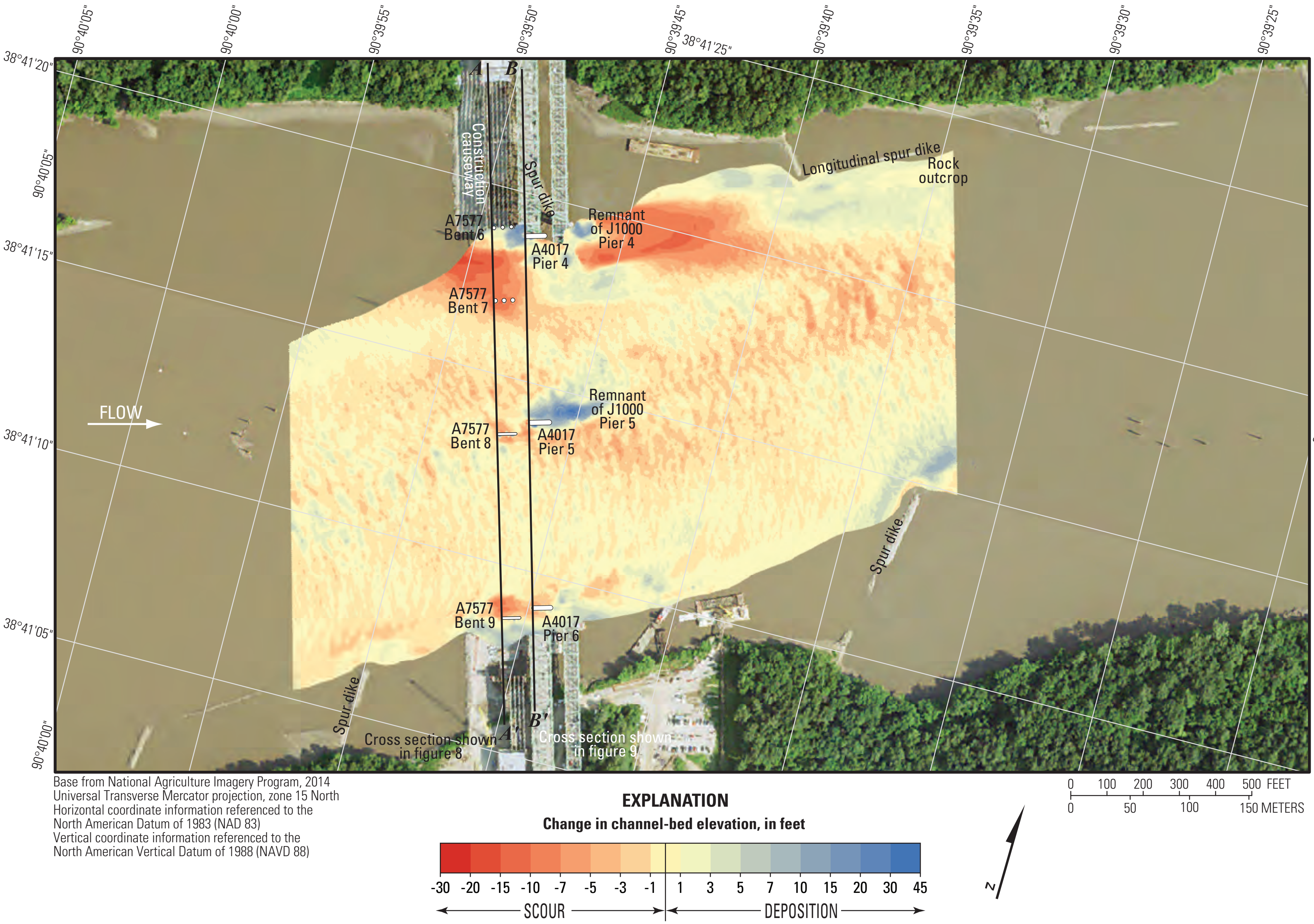


Figure 11. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structures A7577 and A4017 on U.S. Highway 40 near St. Louis, Missouri, on May 23, 2016, and October 18, 2010.

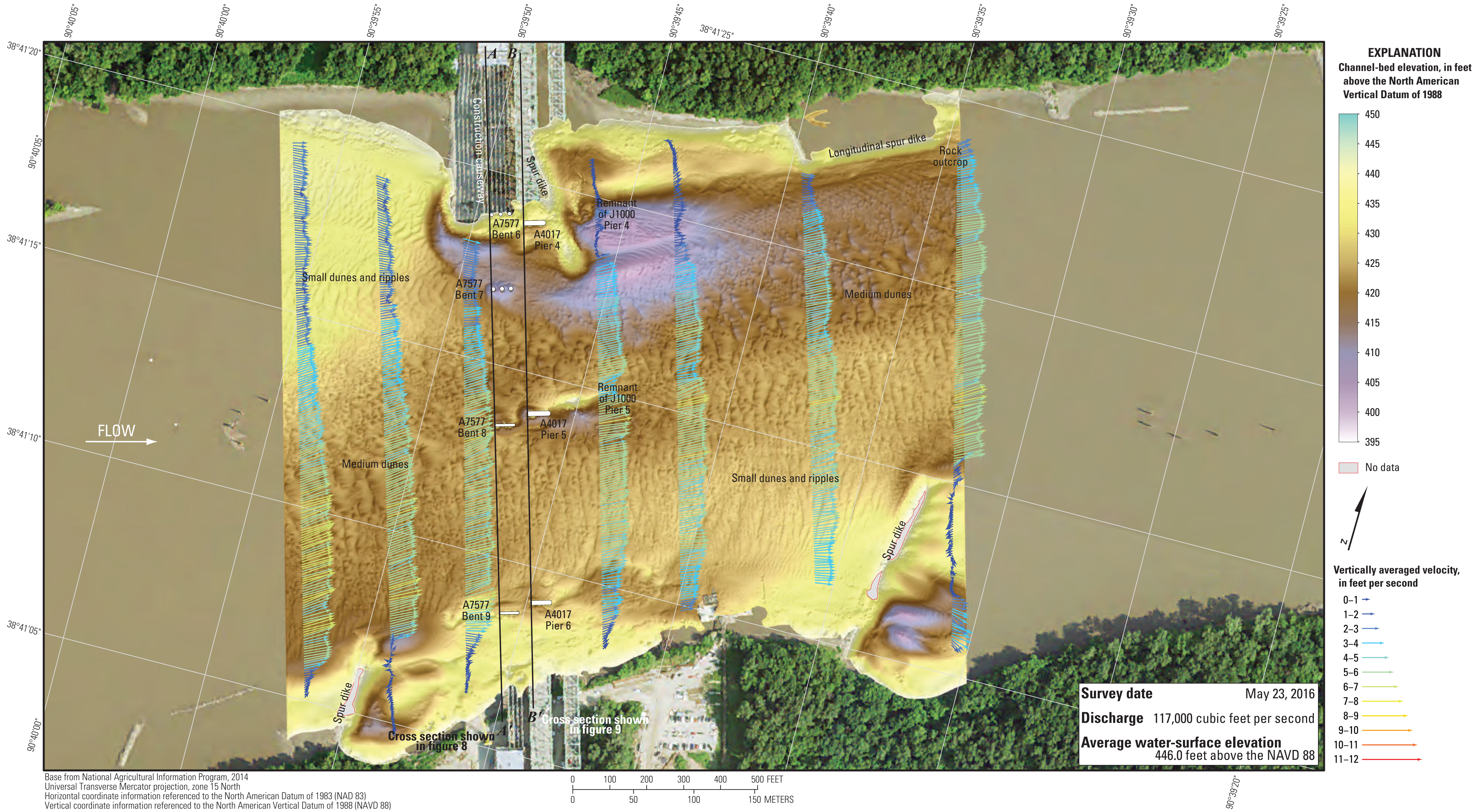


Figure 12. Bathymetry and vertically averaged velocities of the Missouri River channel near structures A7577 and A4017 on U.S. Highway 40 near St. Louis, Missouri.

Dual Bridge Structure A5585 on State Highway 364

Structure A5585 (site 24) consists of twin bridges on State Highway 364, crossing the Missouri River at RM 32.7, on the northwestern side of the St. Louis metropolitan area between Maryland Heights and St. Charles, Mo. (fig. 1). The site was surveyed on May 24, 2016, and the average water-surface elevation near the bridge, determined by the RTK GNSS tide solution, was 434.1 ft (table 5). Flow on the Missouri River was about 110,000 ft^3/s during the survey (table 5), which does not account for flow through a side channel near the site. The flow measured at structures A3292 and L0561 just a little later in the day was about 116,000 ft^3/s, and was 114,000 ft^3/s still later on the same day at dual bridge structure A4557 (table 5).

The survey area was about 1,640 ft long and about 1,230 ft wide, extending from bank to bank in the main channel (fig. 13). The upstream end of the survey area was about 720 ft upstream from the centerline of dual bridge structure A5585 at pier 5 (fig. 13). The approximate channel-bed elevations ranged from about 406 to 424 ft for most of the surveyed area (5th to 95th percentile range of the bathymetric data; table 5; fig. 14), except along the channel thalweg where medium to large dunes caused local approximate minimum channel-bed elevations of about 399 ft (fig. 13; table 5). The thalweg was along the outside of the river bend on the left (north) bank, and was about 10 to 15 ft deeper than the bed in the middle of the channel (fig. 13). Numerous small dunes and ripples were present throughout the middle of the channel, and a nearly planar bed area was present with no prominent features along the right (south) bank (fig. 13). As in previous surveys (Huizinga, 2011, 2012), a rock outcrop was present on the left (north) bank throughout the reach (fig. 13).

Scour holes were present near the main channel piers of structure A5585 (fig. 13), and generally more substantial scour was associated with the upstream (eastbound) piers than the downstream (westbound) piers. The scour hole at upstream (eastbound) pier 5 had a minimum channel-bed elevation of about 406 ft (fig. 13; table 6), about 8 ft below the average channel bed immediately upstream from the pier, whereas the scour hole at downstream (westbound) pier 5 had a minimum channel-bed elevation of about 407 ft (fig. 13; table 6), about 6 ft below the average channel bed immediately upstream from the pier. The scour hole at upstream (eastbound) piers 6 and 7 extended to near the corresponding downstream (westbound) pier. The scour hole at upstream (eastbound) pier 6 had a minimum channel-bed elevation of about 410 ft (fig. 13; table 6), about 6 ft below the average channel bed immediately upstream from the pier, whereas the scour hole at downstream (westbound) pier 6 had a minimum channel-bed elevation of about 407 ft (fig. 13; table 6), about 4 ft below the average channel bed immediately upstream from the pier. The scour hole at upstream (eastbound) pier 7 had a minimum channel-bed elevation of about 420 ft (fig. 13; table 6), whereas the scour hole at downstream (westbound) pier 7 had a minimum channel-bed elevation of about 415 ft (fig. 13; table 6), both of which are only about 3 ft below the average channel bed immediately upstream from the pier.

Information from bridge plans indicates that the main channel piers of both bridges of structure A5585 are founded on shafts drilled 11 ft into bedrock (figs. 15, 16; table 6). Depth of bed material between bedrock and the bottom of the various scour holes at dual bridge structure A5585 ranged from 34 to 69 ft because of the sloping bedrock in the area (figs. 15, 16; table 6). The approximate minimum channel-bed elevation in each of the scour holes was substantially higher than the bottom of the seal course elevation at each pier of 371.62 ft (figs. 15, 16; table 6).

The difference between the survey on May 24, 2016, and the previous survey on August 1, 2011, indicates an approximately even split of aggradation and degradation throughout the reach, except near the rock outcrop on the left (north) bank (fig. 17). Overall, there was minimal net change between the surveys, as indicated by the mean difference being +0.16 ft (table 7). The net volume of cut in the reach from 2011 to 2016 was about 74,700 yd^3, and the net volume of fill was about 86,400 yd^3, resulting in a net gain of about 11,700 yd^3 of sediment between 2011 and 2016. There was net deposition near pier 5 and net scour near pier 6 (figs. 15–17). A substantial scour hole near upstream (eastbound) pier 7 caused in part by debris trapped on that pier in the 2011 survey has filled in (fig. 15), as evidenced by the deposition in a horseshoe shape around the nose of that pier (fig. 17). The frequency distribution of channel-bed elevations was slightly narrower in 2016 than in 2011; a greater percentage of survey-grid cells were present at elevations between 410 and 416 ft than in 2011 (fig. 14). The rock outcrop on the left (north) bank showed no signs of substantial change except for areas of minor deposition on several rock ledges (fig. 17). As stated for the previous site (Structures A7577 and A4017 on U.S. Highway 40), although rock ultimately is an erodible material, its rate of erosion is substantially slower than that of sand and silt (Richardson and Davis, 2001).

Dual Bridge Structure A5585 on State Highway 364.

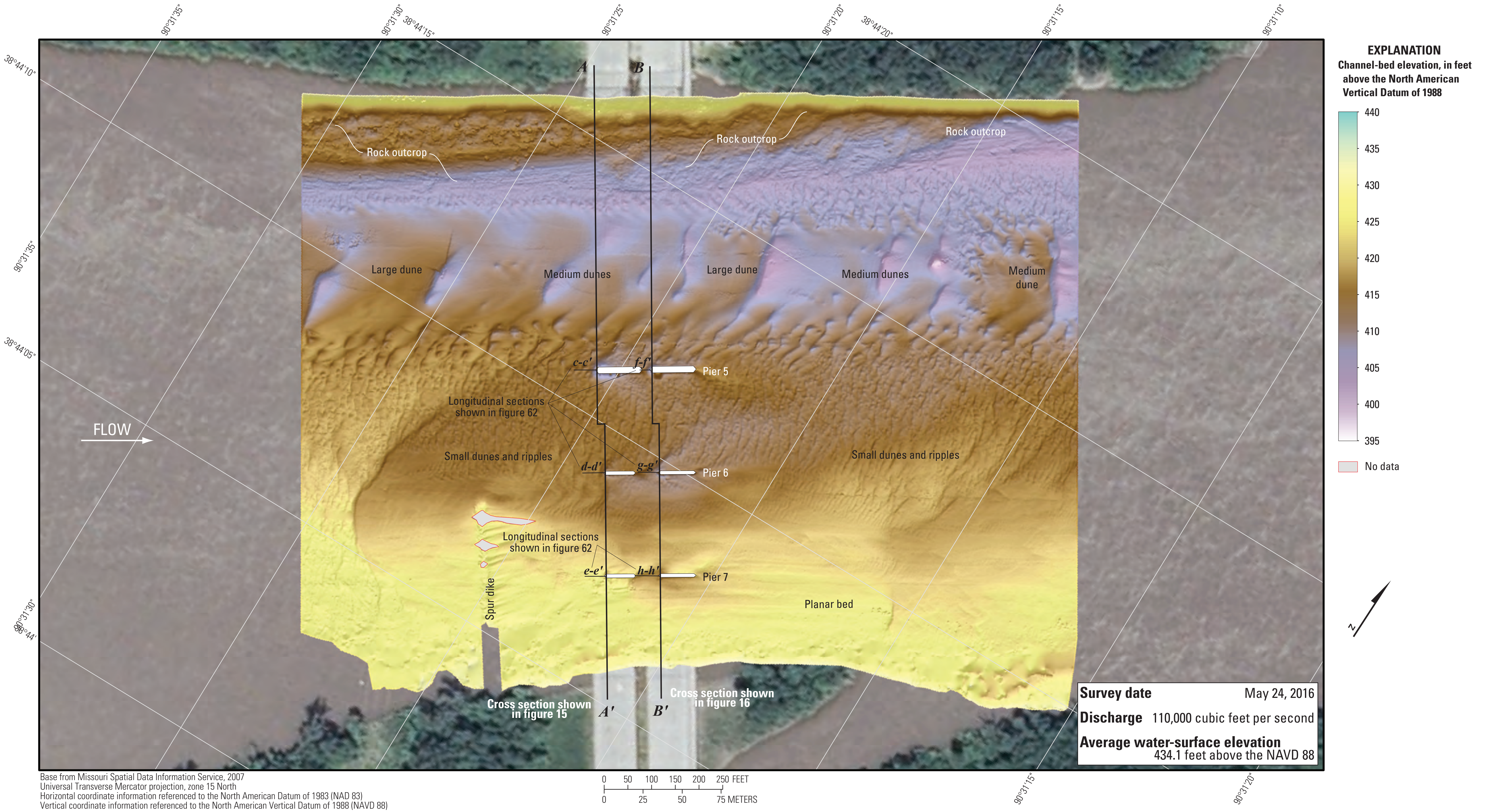


Figure 13. Bathymetric survey of the Missouri River channel near dual bridge structure A5585 on State Highway 364 near St. Louis, Missouri.

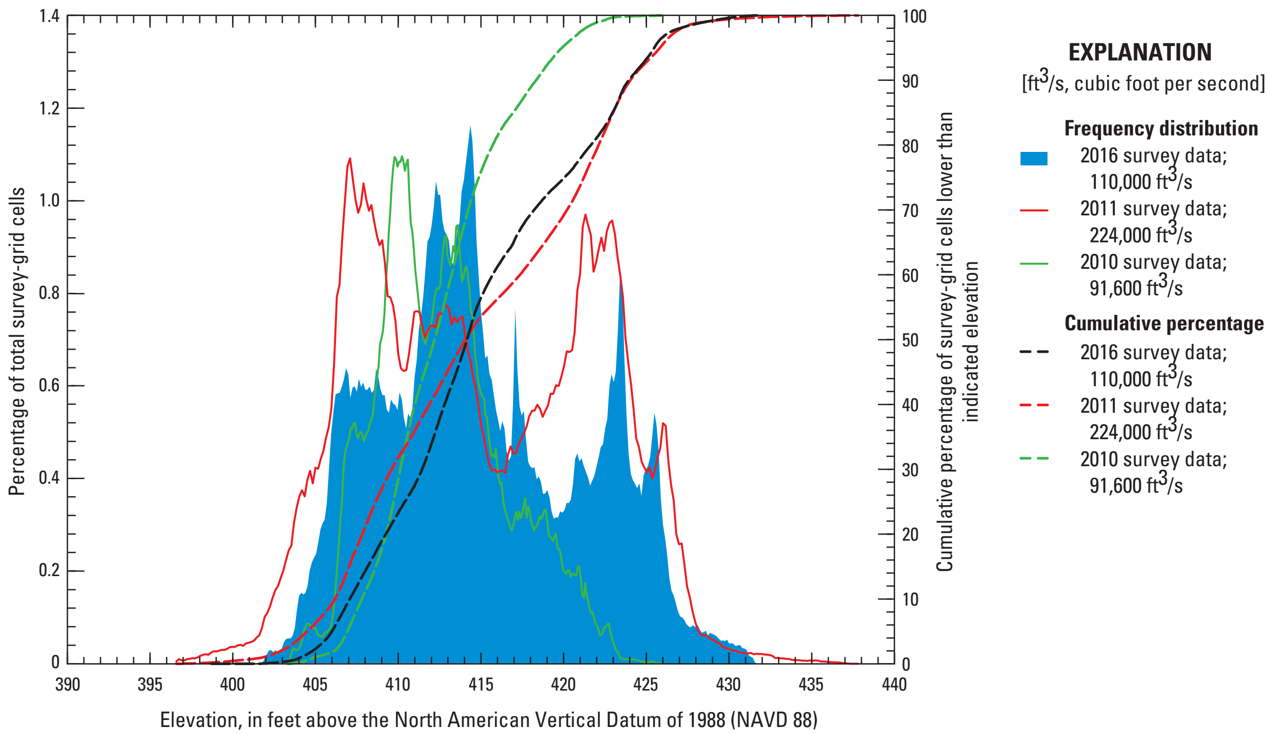


Figure 14. Frequency distribution of bed elevations for bathymetric survey-grid cells on the Missouri River near dual bridge structure A5585 on State Highway 364 near St. Louis, Missouri, on May 24, 2016, compared to previous surveys.

The difference between the survey on May 24, 2016, and the previous nonflood survey on October 21, 2010 (fig. 18), indicates very minor scour throughout the reach from the 2010 to 2016 surveys, resulting in a mean difference of –0.24 ft between the bathymetric surfaces (table 7). The net volume of cut in the reach from 2010 to 2016 was about 49,800 yd^3, and the net volume of fill was about 36,600 yd^3, resulting in a net loss of about 13,200 yd^3 of sediment between 2010 and 2016. The flow conditions of the 2010 survey were similar to the 2016 survey (table 7), which may help explain the similarity between the surveys; however, the frequency distribution of bed elevations was substantially wider in 2016 than in 2010, because a greater percentage of survey-grid cells were present at elevations above 420 ft than in 2010 (fig. 14).

The vertically averaged velocity vectors indicate moderate to substantial turbulence throughout the reach, ranging from about 2 to 10 ft/s (fig. 19). Flow was angled to the left (north) in the upstream reach because of the bend in the river, and numerous local velocity minima were on the right (south) side of the channel (fig. 19). Substantial turbulence was observed in the channel thalweg, particularly downstream from the bridges (fig. 19). Piers 5 through 7 were aligned with flow, resulting in minimal additional turbulence downstream (fig. 19).

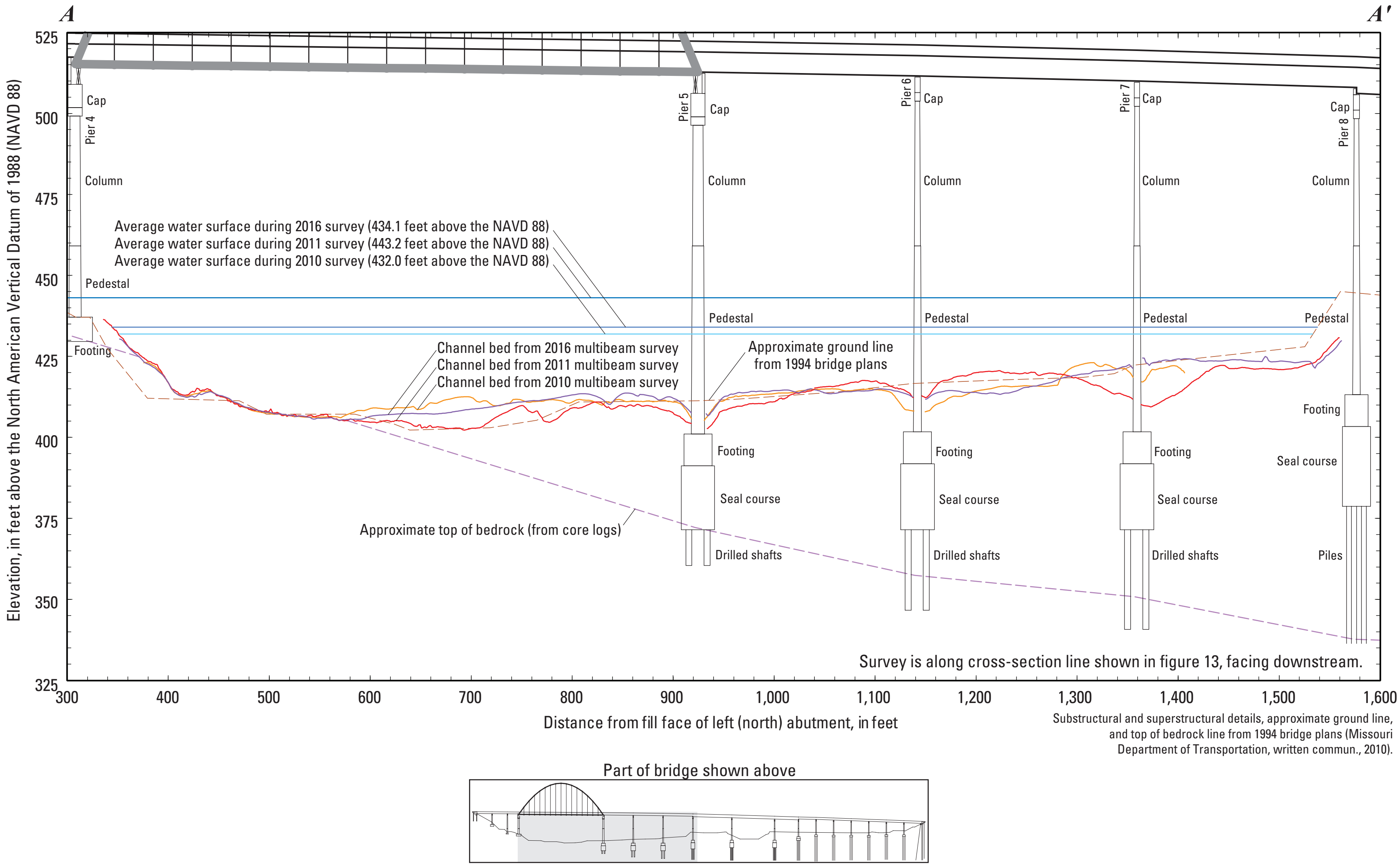


Figure 15. Key features, substructural and superstructural details, and surveyed channel bed along the upstream face of the upstream bridge of dual bridge structure A5585 on State Highway 364 crossing the Missouri River near St. Louis, Missouri.

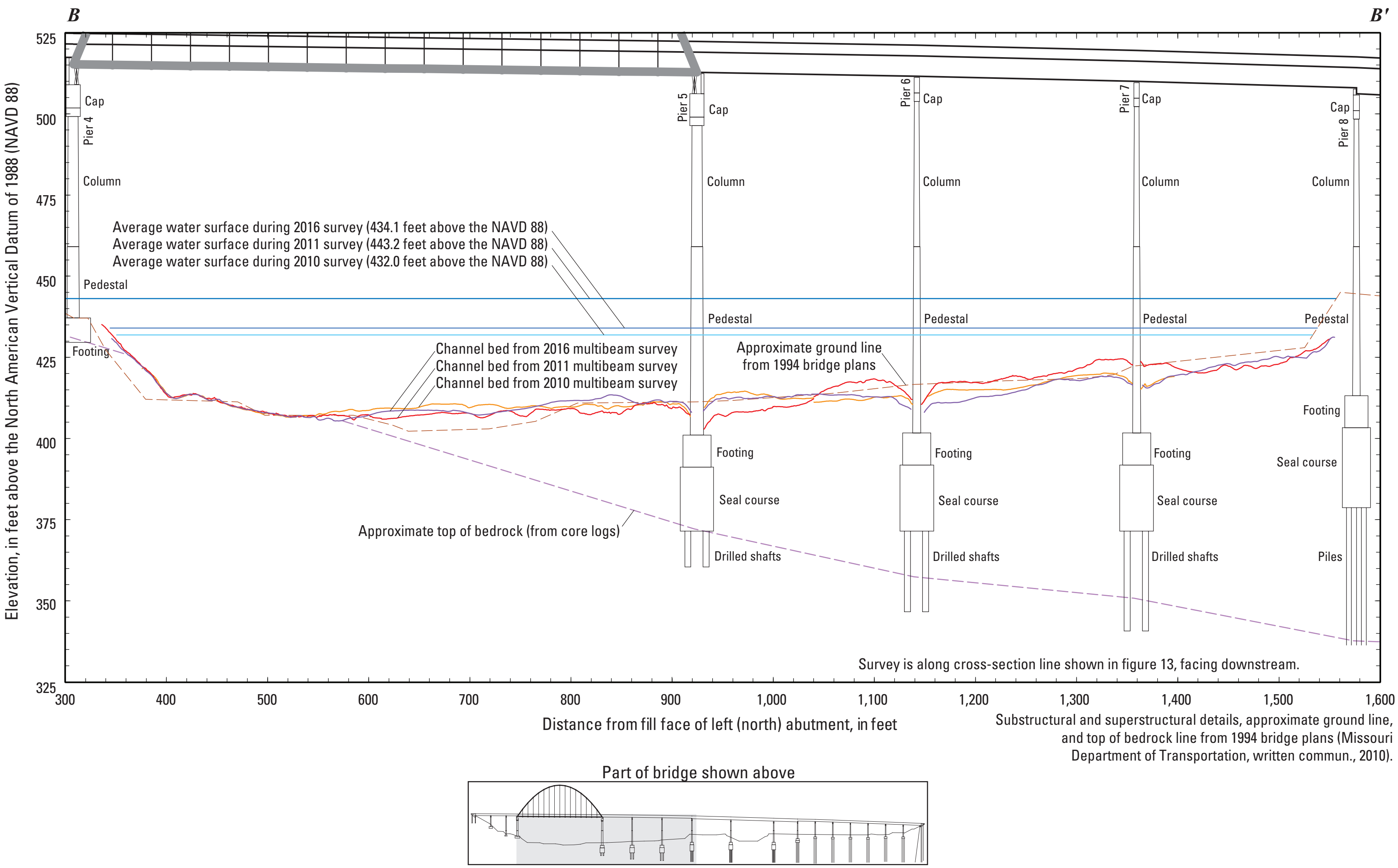


Figure 16. Key features, substructural and superstructural details, and surveyed channel bed along the upstream face of the downstream bridge of dual bridge structure A5585 on State Highway 364 crossing the Missouri River near St. Louis, Missouri.

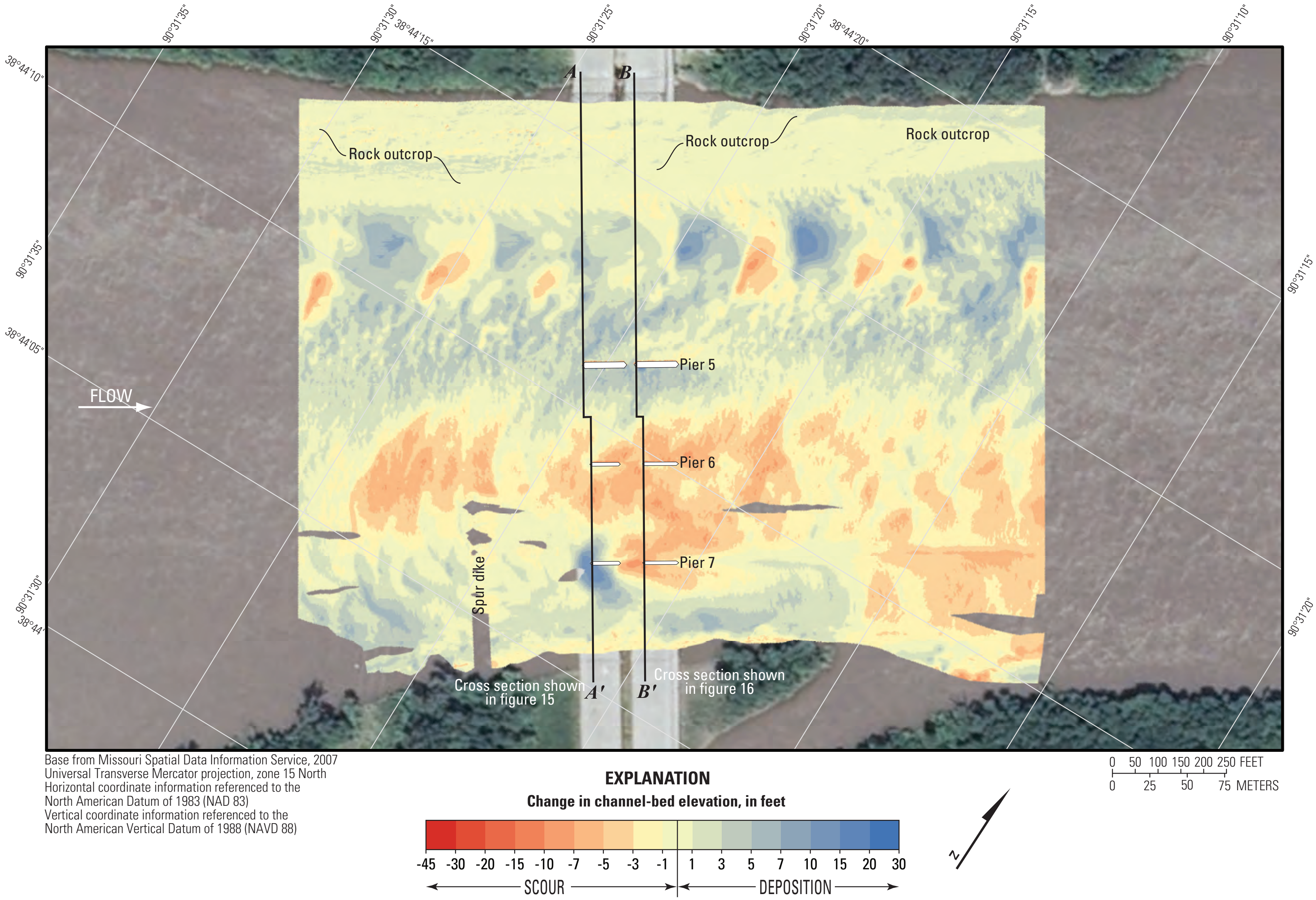


Figure 17. Difference between surfaces created from bathymetric surveys of the Missouri River channel near dual bridge structure A5585 on State Highway 364 near St. Louis, Missouri, on May 24, 2016, and August 1, 2011.

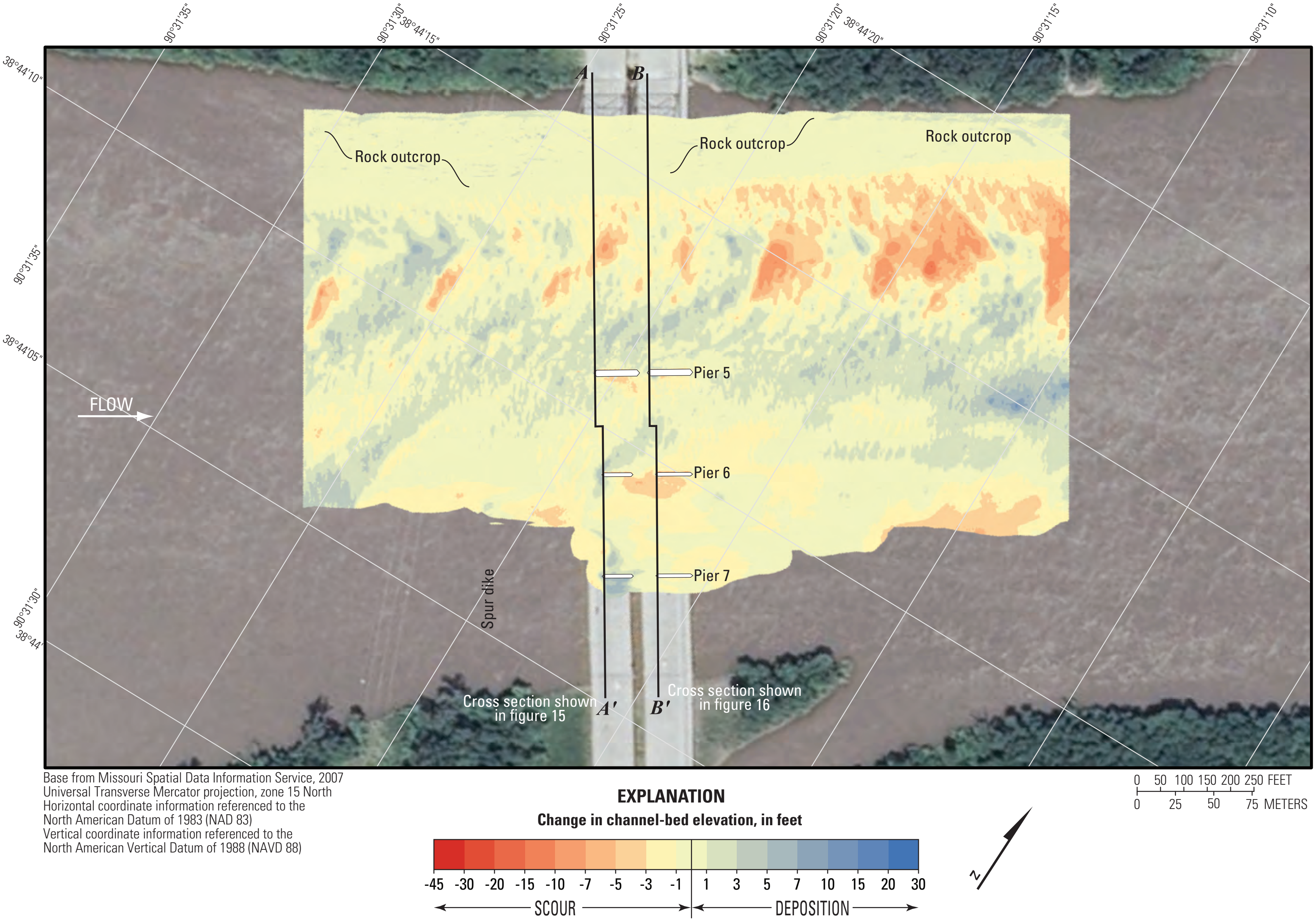


Figure 18. Difference between surfaces created from bathymetric surveys of the Missouri River channel near dual bridge structure A5585 on State Highway 364 near St. Louis, Missouri, on May 24, 2016, and October 21, 2010.

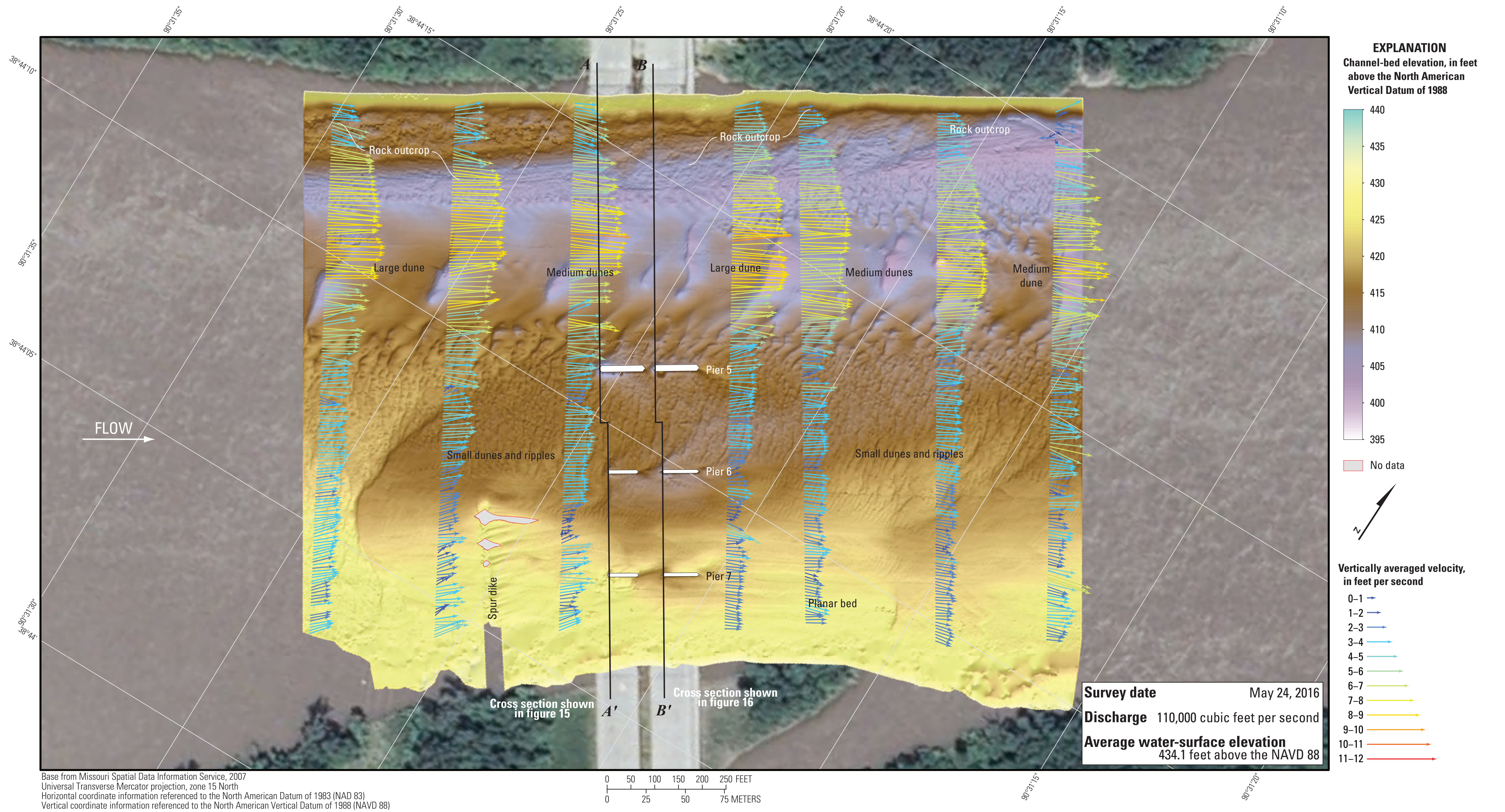


Figure 19. Bathymetry and vertically averaged velocities of the Missouri River channel near dual bridge structure A5585 on State Highway 364 near St. Louis, Missouri.

Structures A3292 and L0561 on Interstate 70

Structures A3292 and L0561 (site 25) are dual bridges on Interstate 70, crossing the Missouri River at RM 29.6, on the northwestern side of the St. Louis metropolitan area between Maryland Heights and St. Charles, Mo. (fig. 1). The site was surveyed on May 24, 2016, and the average water-surface elevation near the bridge, determined by the RTK GNSS tide solution, was 431.8 ft (table 5). Flow on the Missouri River was about 116,000 ft^3/s during the survey (table 5).

The survey area was about 1,640 ft long and varied in width from about 1,490 ft wide at the upstream end to about 1,070 ft wide at the downstream end, extending from bank to bank in the main channel (fig. 20). The upstream end of the survey area was about 690 ft upstream from the centerline of structures A3292 and L0561 (fig. 20). The approximate channel-bed elevations ranged from about 404 to 423 ft for most of the surveyed area (5th to 95th percentile range of the bathymetric data; table 5; fig. 21), except downstream from the spur dike on the left (northwest) bank downstream from the bridge, near the piers, and in the downstream channel thalweg (fig. 20). The thalweg was on the right (southeast) bank throughout the reach and was about 8 to 15 ft deeper than the channel bed in the middle of the channel (fig. 20). The channel and thalweg deepened downstream from the bridges (fig. 20), likely because of the contraction of the channel caused by the building on the left bank downstream from the bridges. On the upstream left (northwest) side, deposits reached an elevation of about 423 ft (fig. 20). A line of medium dune features were detected in the middle of the channel through the survey reach, and numerous smaller dunes and ripples were present throughout the channel reach (fig. 20). A localized deep scour hole at the end of the shallow spur dike between the downstream bridge and the building on the left bank had a minimum channel-bed elevation of about 397 ft (fig. 20). As in previous surveys (Huizinga, 2011, 2012), stone revetment was present on the right (southeast) bank throughout the reach (fig. 20).

A minor scour hole near the left main channel piers (pier 15 of upstream structure A3292 and pier 16 of downstream structure L0561; fig. 20) had an approximate minimum channel-bed elevation of about 407 and 409 ft, respectively (table 6), about 13 ft below the average channel bed immediately upstream from pier 15 of structure A3292 (fig. 20; table 6). The scour hole was deeper on the right (southeast) side of pier 15 (fig. 20), likely exacerbated by the effects of a small debris raft trapped on the nose of that pier and the angled flow near the left main channel piers caused by the constriction downstream (fig. 22). Information from bridge plans indicates that pier 15 of upstream structure A3292 is founded on shafts drilled about 16 ft in bedrock (table 6), and about 57 ft of bed material was present between the bottom of the scour hole and bedrock near the upstream pier (fig. 23; table 6). Pier 16 of downstream structure L0561 is founded on a caisson on bedrock, and the bottom of the minor local scour hole near this pier was about 58 ft above the bottom of the caisson and bedrock (fig. 24; table 6).

Larger scour holes were present near the right main channel piers of structures A3292 and L0561 (fig. 20). The scour hole at upstream pier 16 had an approximate minimum channel-bed elevation of about 399 ft (fig. 23; table 6), about 12 ft below the average channel bed immediately upstream from the pier, whereas the scour hole at downstream pier 17 had an approximate minimum channel-bed elevation of about 389 ft (fig. 24; table 6), about 18 ft below the average channel bed immediately upstream from that pier. Information from bridge plans indicates that pier 16 of upstream structure A3292 is founded on shafts drilled 17 ft into bedrock, and about 57 ft of bed material was present between the bottom of the scour hole and bedrock (fig. 23; table 6). Pier 17 of structure L0561 is founded on a caisson on bedrock, and about 46 ft of bed material was present between the bottom of the scour hole and bedrock (fig. 24; table 6).

The vertically averaged velocity vectors indicate mostly uniform flow throughout the channel, ranging from about 3 to 8 ft/s (fig. 22). Flow was angled to the right (southeast) in the upstream reach because of the downstream contraction (fig. 22). Exceptions to uniform conditions include substantial turbulence observed downstream from the right (southeast) main channel piers of structures A3292 and L0561 and minor turbulence in the downstream-most transect (fig. 22). The right main channel piers were aligned with flow, whereas the left main channel piers were not.

The difference between the survey on May 24, 2016, and the previous survey on August 2, 2011 (fig. 25), indicates moderate deposition throughout the reach from 2011 to 2016, resulting in a mean difference of +2.23 ft between the bathymetric surfaces (table 7). The net volume of cut in the reach from 2011 to 2016 was about 26,000 yd^3, and the net volume of fill was about 188,800 yd^3, resulting in a net gain of about 162,800 yd^3 of sediment between 2011 and 2016. Moderate to substantial scour had been observed between the 2010 and 2011 surveys (Huizinga, 2012), but ongoing sediment transport processes seem to have fully replenished the sediment deposits at this site. There was substantial deposition in the scour hole caused by a sizable debris raft upstream from pier 15 of structure A3292 (fig 25; Huizinga, 2012). Areas of moderate scour were present downstream from the spur dike and along the left (northwest) bank downstream from the bridges at the constriction, and minor localized scour of the deposits was present along the upstream left (northwest) bank (fig. 25).

Structures A3292 and L0561 on Interstate 70.

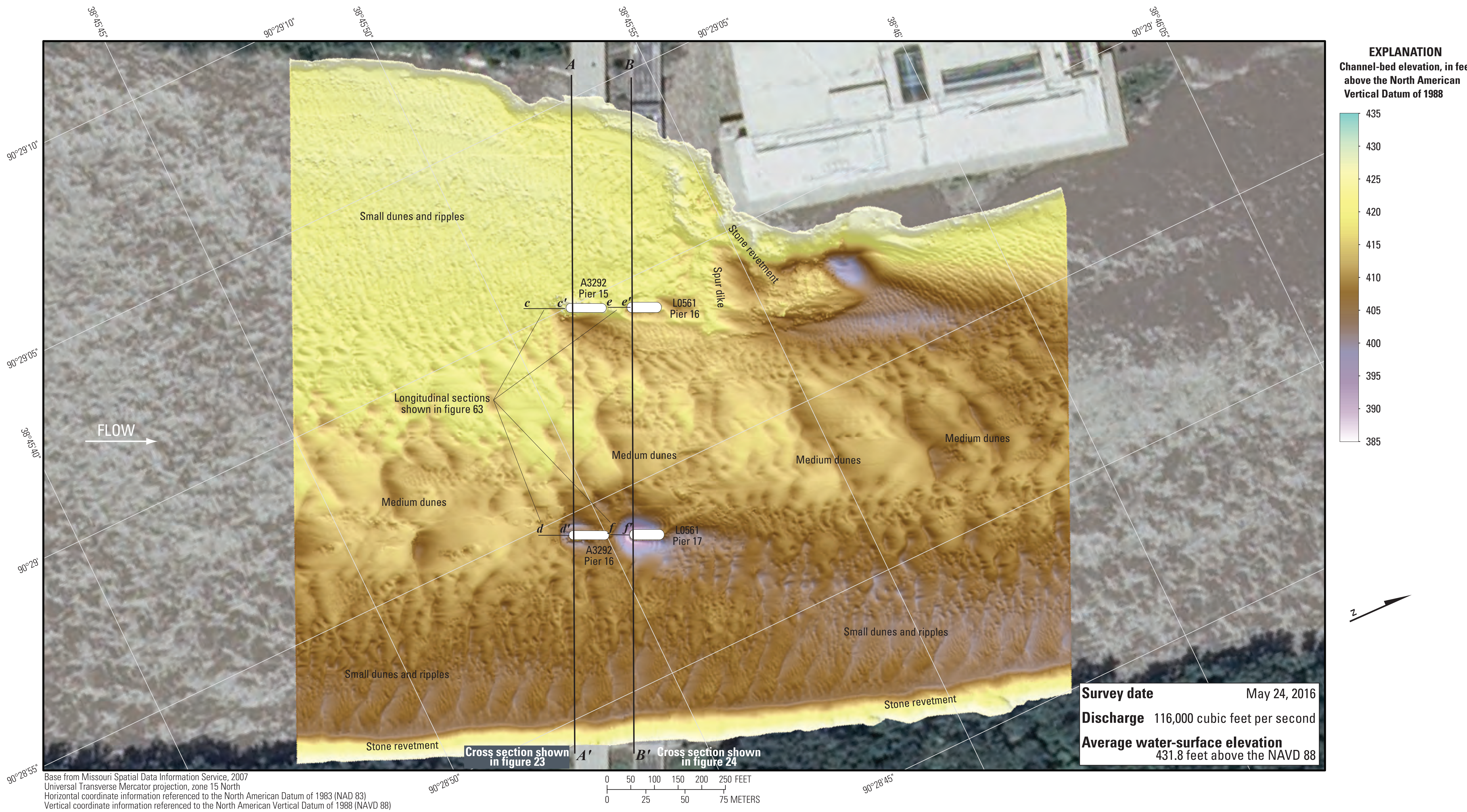


Figure 20. Bathymetric survey of the Missouri River channel near structures A3292 and L0561 on Interstate 70 near St. Louis, Missouri.

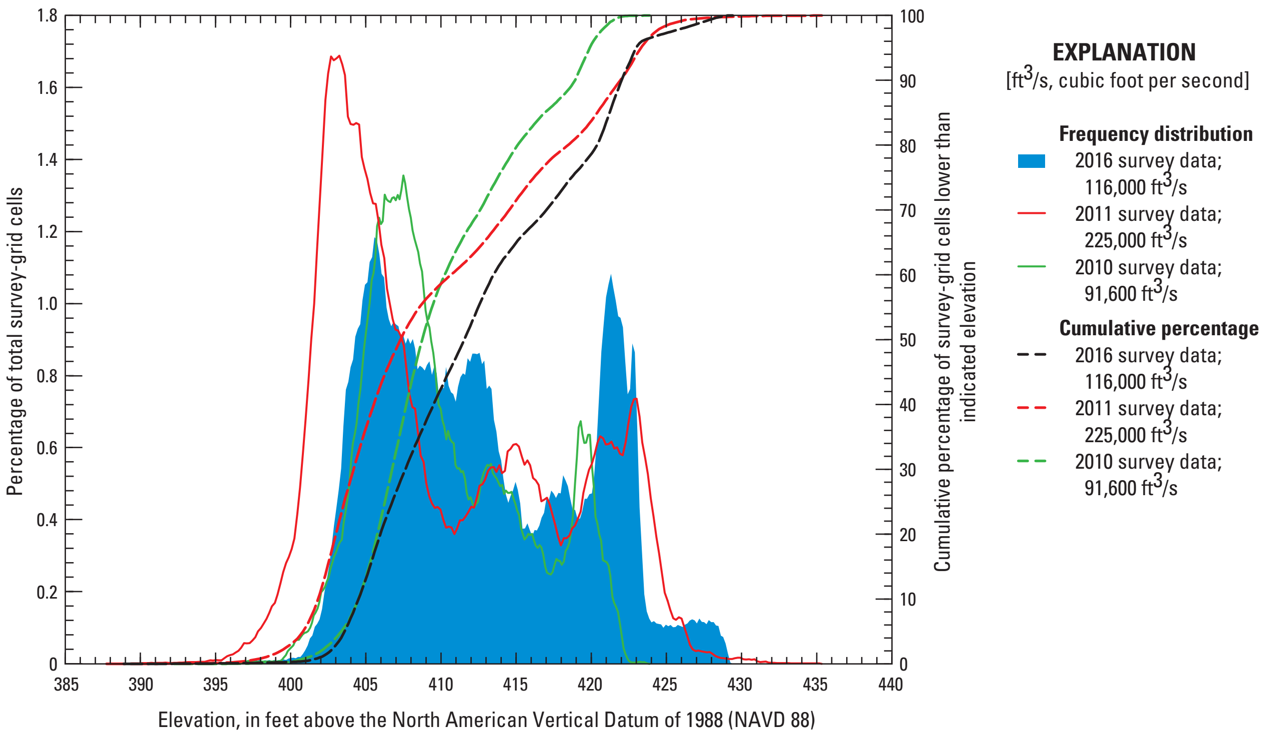


Figure 21. Frequency distribution of bed elevations for bathymetric survey-grid cells on the Missouri River near structures A3292 and L0561 on Interstate 70 near St. Louis, Missouri, on May 24, 2016, compared to previous surveys.

The cross sections from the 2016 survey show the pattern of deposition in the thalweg and scour on the left (northwest) side of the channel compared to the 2011 survey (figs. 23, 24). The frequency distribution of bed elevations was narrower in 2016 than in 2010; however, a greater percentage of survey-grid cells were present at elevations between 420 and 424 ft than in 2011 (fig. 21). The stone revetment on the upstream right (southeast) bank seems to have experienced deposition, whereas the revetment near the bridge seems to have experienced minor scour (fig. 25), but this may be a function of positional variations between the surveys. Huizinga (2011) noted issues with horizontal positioning at this site during the survey in October 2010. Substantial deposition or scour apparent at the faces of the piers likely results from minor horizontal positional variances between the surveys (see the "Uncertainty Estimation" section).

The difference between the survey on May 24, 2016, and the previous nonflood survey on October 21, 2010 (fig. 26), does not indicate substantial bed variation from 2010 to 2016, resulting in a mean difference of +0.86 ft between the bathymetric surfaces (table 7). The net volume of cut in the reach from 2010 to 2016 was about 33,000 yd^3, and the net volume of fill was about 89,000 yd^3, resulting in a net gain of about 56,000 yd^3 of sediment between 2010 and 2016. There was substantial deposition in the scour hole caused by a debris raft upstream from pier 15 of structure A3292 (Huizinga, 2011) and in the middle of the channel at and immediately downstream from the bridges (fig. 26). Moderate localized scour was observed near the right main channel piers and along the toe of the upstream right (southeast) bank (fig. 26). The cross sections from the two surveys further indicate the general similarities (figs. 23, 24). The frequency distribution of bed elevations was similar in shape but slightly wider in 2016 than in 2010, and a greater percentage of survey-grid cells were at a higher elevation in 2016 than 2010 (fig. 21). The localized scour observed on the stone revetment on the right (southeast) bank in 2011 (Huizinga, 2012) is present in the difference between the 2016 and 2010 surveys (fig. 26), but this difference may be a function of positional variations between the surveys. Huizinga (2011) noted issues with horizontal positioning at this site during the survey in October 2010. As with all difference maps in this report, substantial deposition or scour apparent at the faces of the piers results from minor horizontal positional variances between the surveys (see the "Uncertainty Estimation" section).

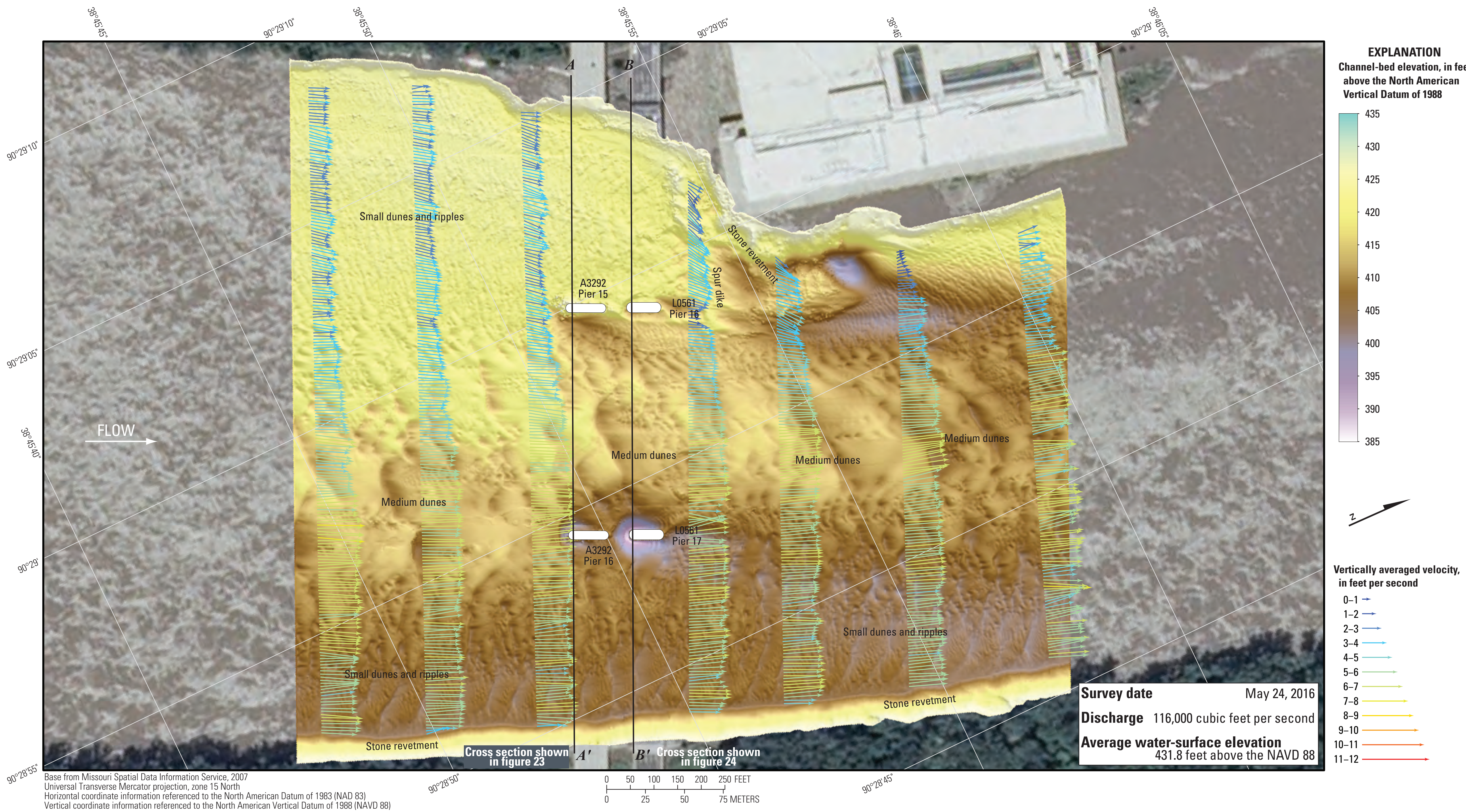


Figure 22. Bathymetry and vertically averaged velocities of the Missouri River channel near structures A3292 and L0561 on Interstate 70 near St. Louis, Missouri.

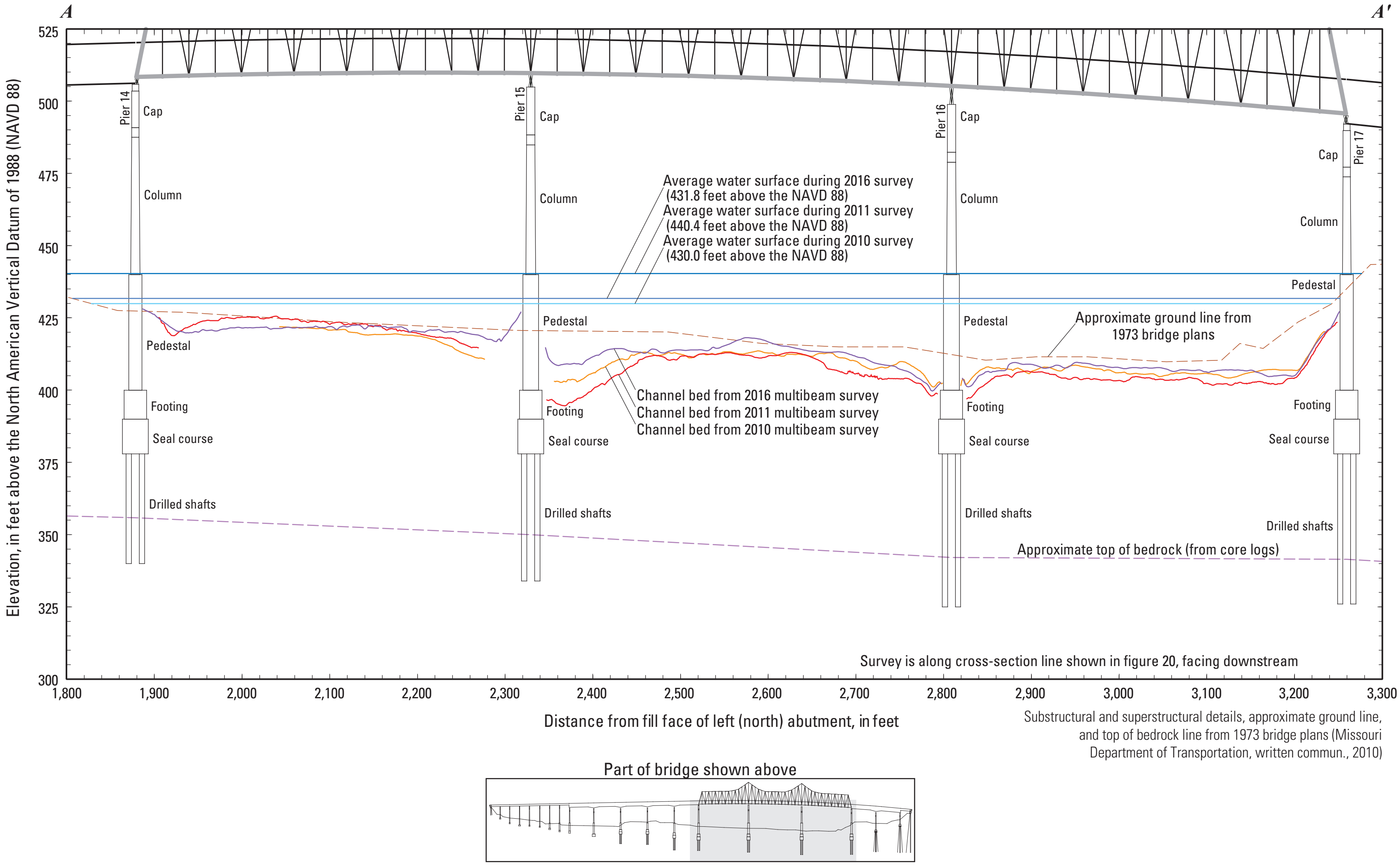


Figure 23. Key features, substructural and superstructural details, and surveyed channel bed of structure A3292 on Interstate 70 crossing the Missouri River near St. Louis, Missouri.

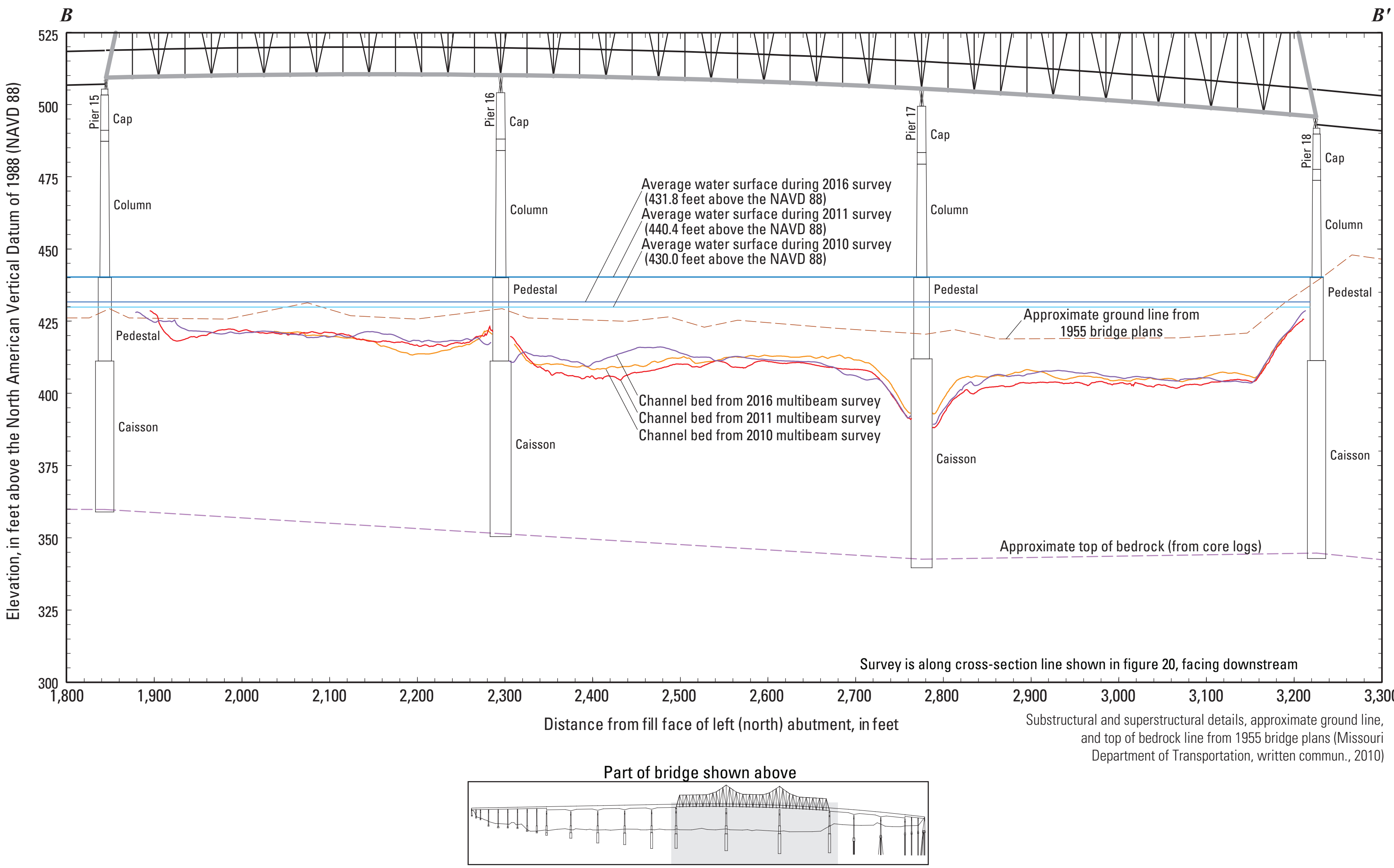


Figure 24. Key features, substructural and superstructural details, and surveyed channel bed of structure L0561 on Interstate 70 crossing the Missouri River near St. Louis, Missouri.

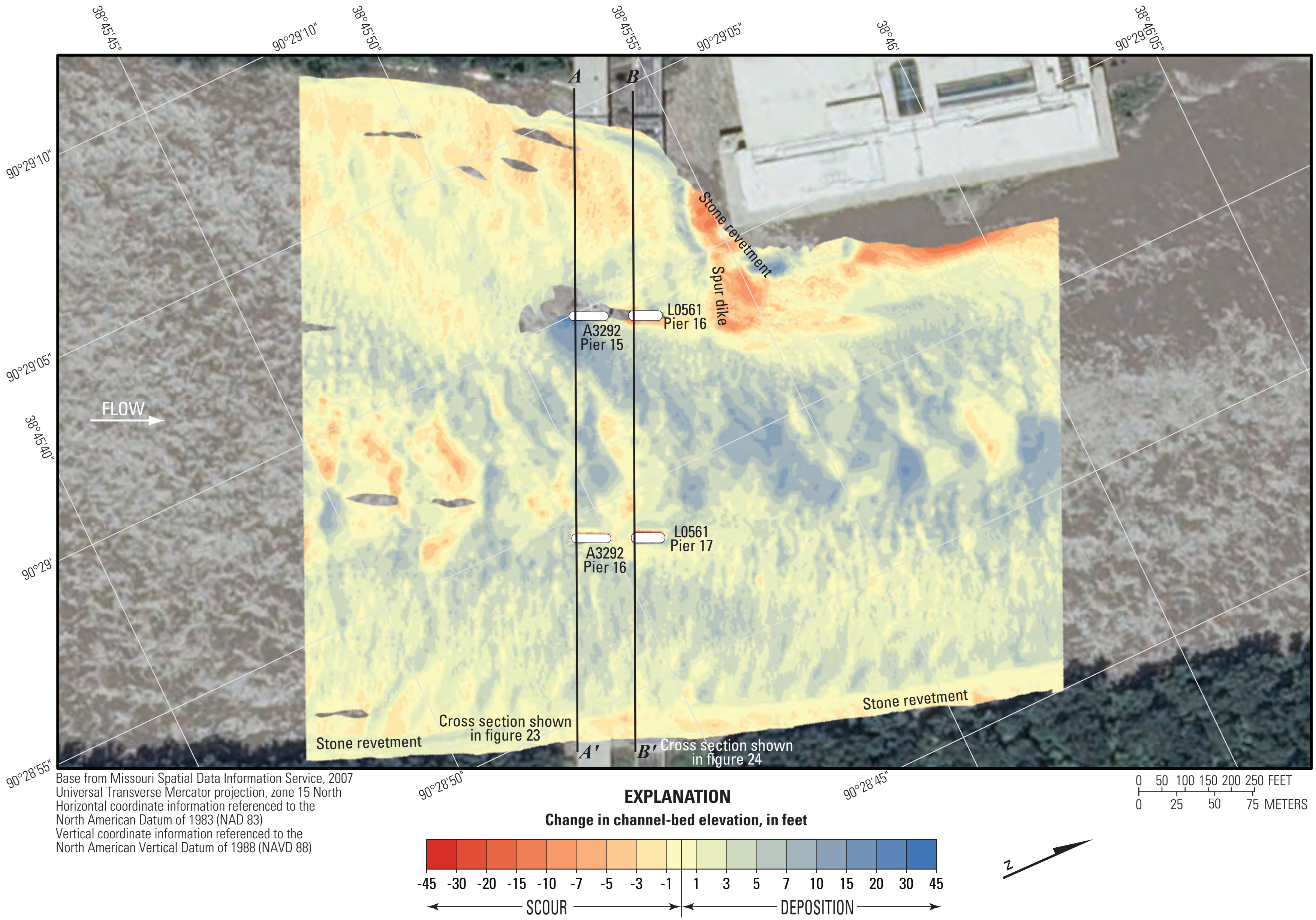


Figure 25. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structures A3292 and L0561 on Interstate 70 near St. Louis, Missouri, on May 24, 2016, and August 2, 2011.

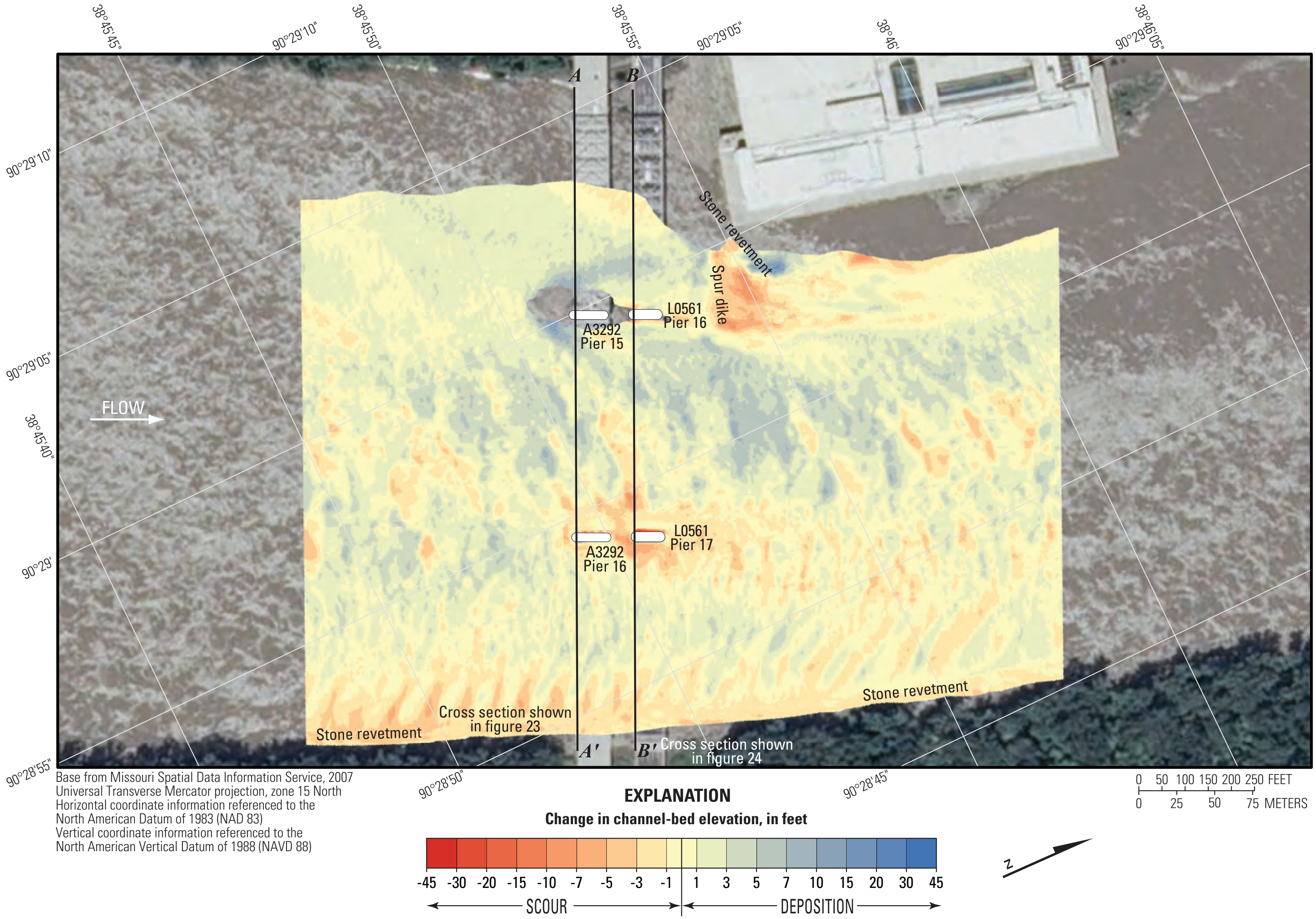


Figure 26. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structures A3292 and L0561 on Interstate 70 near St. Louis, Missouri, on May 24, 2016, and October 21, 2010.

Dual Bridge Structure A4557 on State Highway 370

Structure A4557 (site 26) consists of twin bridges on State Highway 370, crossing the Missouri River at RM 27.0, on the northwestern side of the St. Louis metropolitan area between Bridgeton and St. Charles, Mo. (fig. 1). The site was surveyed on May 24, 2016, and the average water-surface elevation near the bridge, determined by the RTK GNSS tide solution, was 429.9 ft (table 5). Flow on the Missouri River was about 114,000 ft^3/s during the survey (table 5).

The survey area was about 1,640 ft long and about 1,280 ft wide, extending from bank to bank in the main channel (fig. 27). The upstream end of the survey area was about 670 ft upstream from the centerline of structure A4557 (fig. 27). The approximate channel-bed elevations ranged from about 399 to 417 ft for most of the surveyed area (5th to 95th percentile range of the bathymetric data; table 5; fig. 28), except near the piers and along the toe of the rock outcrop along the left (northwest) side of the channel, which had a minimum channel-bed elevation of about 392 ft (fig. 27). The approximate minimum channel-bed elevation of 388 ft was at the bottom of the scour hole at the railroad bridge pier upstream from pier 2C (fig. 27; table 5). A series of medium dune features were observed in the channel thalweg, with numerous small dunes and ripples detected throughout most of the rest of the channel, and a nearly planar bed area with no prominent features along the right (southeast) bank (fig. 27). As in previous surveys (Huizinga, 2011, 2012), a spur dike was present under the downstream bridge on the right (southeast) bank (fig. 27).

Small scour holes were present near the main channel piers, except those near the spur dike on the right side of the channel (pier 4C at both bridges; fig. 27). At pier 2C, the scour hole near the upstream (eastbound) pier had a minimum channel-bed elevation of about 403 ft (fig. 27; table 6), about 4 ft below the average channel bed immediately upstream from the pier; and the scour hole at the downstream (westbound) pier had a minimum channel-bed elevation of about 401 ft (fig. 27; table 6), about 6 ft below the average channel bed immediately upstream from the pier. At pier 3C, the scour hole at the upstream pier had a minimum channel-bed elevation of about 402 ft (fig. 27; table 6), about 6 ft below the average channel bed immediately upstream from the pier; and the scour hole at the downstream pier also had a minimum channel-bed elevation of about 402 ft (fig. 27; table 6), about 6 ft below the average channel bed immediately upstream from that pier. Essentially, no scour hole was present around either upstream or downstream pier 4C (fig. 27); however, the spur dike adjacent to these piers caused a local deep hole that reached a minimum channel-bed elevation of about 403 ft downstream from the westbound pier (fig. 27; table 6). These piers essentially were embedded in the rock of the dike, which will limit or prevent additional scour near them. Material from the toe of the spur dike extended to downstream (westbound) pier 3C and may limit scour on the right (south) side of that pier as well; however, flow seems to be deflected towards the left (north) upstream from pier 3C (fig. 29) and may affect the scour hole near these piers.

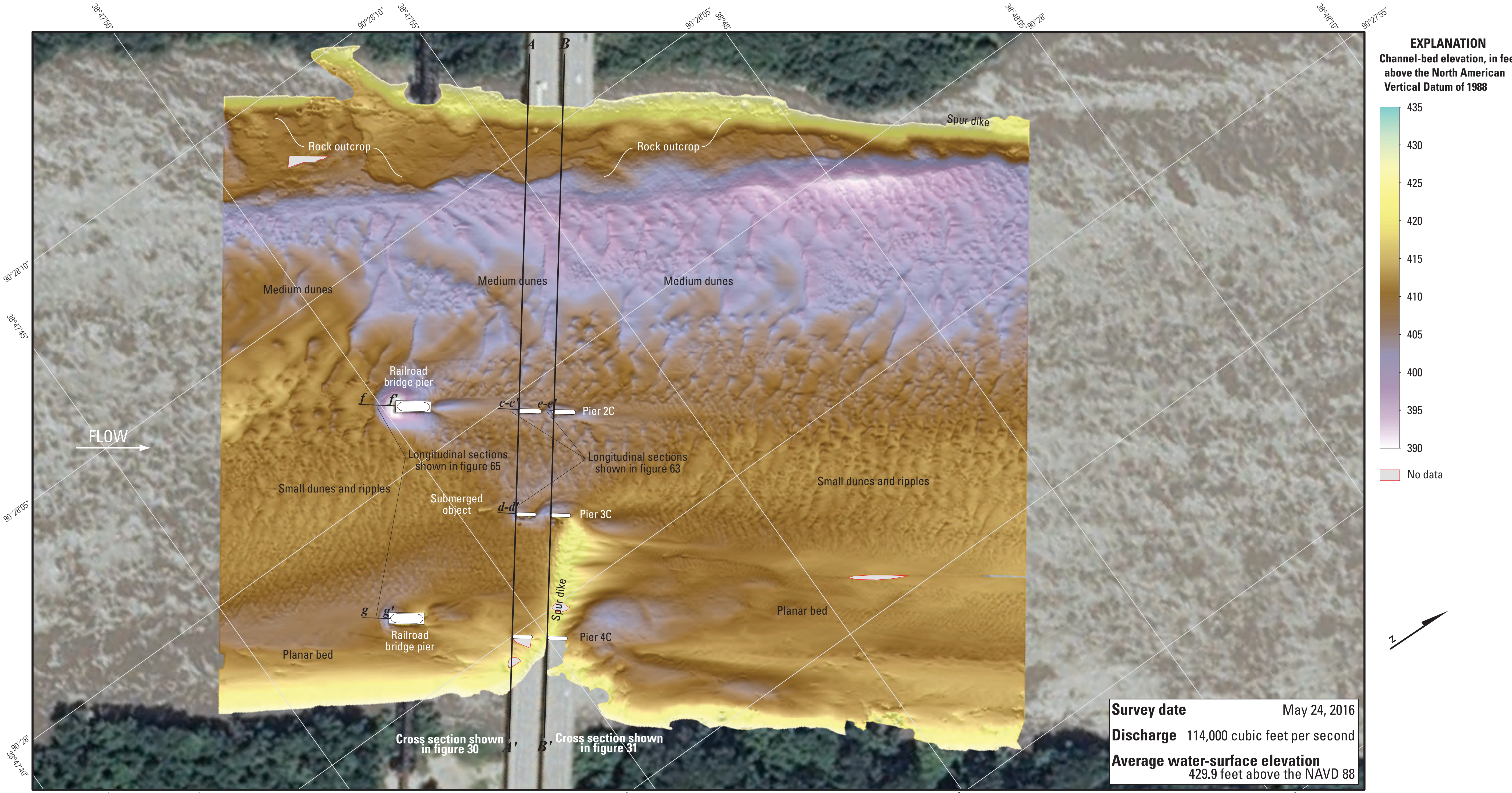
The vertically averaged velocity vectors indicate mostly uniform flow throughout most of the reach, ranging from about 2 to 8 ft/s (fig. 29). Exceptions to uniform conditions include flow reversal on the right (southeast) bank downstream from the spur dike (fig. 29). Moderate turbulence also was observed in the downstream-most transect (fig. 29). All the piers were aligned with flow, as indicated by little to no turbulence observed downstream that can be directly attributed to the piers (fig. 29).

A substantial scour hole was observed at the railroad bridge pier upstream from pier 2C (fig. 27). The hole had a minimum channel-bed elevation of 388 ft at the nose of the pier, about 23 ft below the average channel bed immediately upstream from the pier (fig. 27). A smaller scour hole also was present at the railroad bridge pier upstream from pier 4C, which had a minimum channel-bed elevation of 403 ft at the nose of the pier, about 5 ft below the average channel bed immediately upstream from the pier (fig. 27). The scour holes at the railroad bridge piers did not seem to affect the scour at piers 2C or 4C of structure A4557 (fig. 27).

Information from bridge plans indicates that the main channel piers of both bridges of structure A4557 are founded on shafts drilled 15 ft into bedrock (figs. 30, 31; table 6). Depth of bed material between bedrock and the bottom of the various scour holes at dual bridge structure A4557 ranged from 43 to 66 ft because of the sloping bedrock and channel bed in the area (figs. 30, 31; table 6). The minimum channel-bed elevation in each of the scour holes was more than 9 ft higher than the bottom of the seal course elevation at each pier (figs. 30, 31; table 6).

The difference between the survey on May 24, 2016, and the previous survey on August 2, 2011 (fig. 32), does not indicate substantial bed variation from 2011 to 2016, as indicated by a mean difference of only –0.07 ft between the bathymetric surfaces (table 7). The net volume of cut in the reach from 2011 to 2016 was about 44,600 yd^3, and the net volume of fill was about 39,800 yd^3, resulting in a net loss of only about

Dual Bridge Structure A4557 on State Highway 370.



Base from Missouri Spatial Data Information Service, 2007
Universal Transverse Mercator projection, zone 15 North
Horizontal coordinate information referenced to the North American Datum of 1983 (NAD 83)
Vertical coordinate information referenced to the North American Vertical Datum of 1988 (NAVD 88)

0 50 100 150 200 250 FEET
0 25 50 75 METERS

Figure 27. Bathymetric survey of the Missouri River channel near dual bridge structure A4557 on State Highway 370 near St. Louis, Missouri.

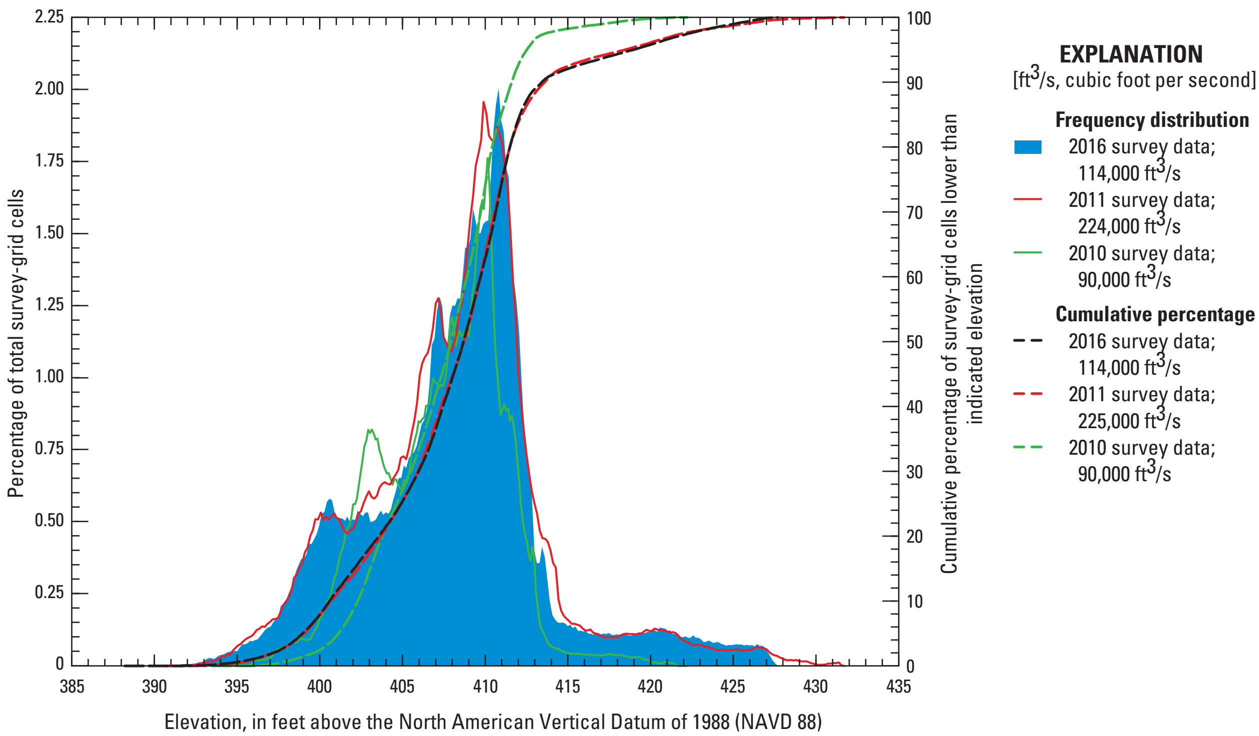


Figure 28. Frequency distribution of bed elevations for bathymetric survey-grid cells on the Missouri River near dual bridge structure A4557 on State Highway 370 near St. Louis, Missouri, on May 24, 2016, compared to previous surveys.

4,800 yd^3 of sediment between 2011 and 2016. There was an area of scour around the railroad bridge pier upstream from pier 2C and an area of deposition in the middle of the channel upstream from the railroad bridge (fig. 32). The cross sections from the two surveys were similar to one another except in the area between the left bank and pier 2C (figs. 30, 31). The frequency distribution of bed elevations were of remarkably similar shape in all three of the surveys to date at this site (fig. 28), despite the difference in discharge (table 7). The rock outcrop on the downstream left (northwest) bank showed no signs of substantial change except for minor deposition along the toe of the bank (fig. 32). As with all difference maps in this report, substantial deposition or scour apparent at the faces of the piers results from minor horizontal positional variances between the surveys (see the “Uncertainty Estimation” section).

The difference between the survey on May 24, 2016, and the previous nonflood survey on October 22, 2010 (fig. 33), also does not indicate substantial bed variation from 2010 to 2016, as indicated by a mean difference of only –0.20 ft between the bathymetric surfaces (table 7). The net volume of cut in the reach from 2010 to 2016 was about 47,000 yd^3, and the net volume of fill was about 33,300 yd^3, resulting in a net loss of only about 13,700 yd^3 of sediment between 2010 and 2016. There was an area of scour around the railroad bridge pier upstream from pier 2C, and some additional scour in the thalweg downstream from the bridges; however, an area of deposition was present in the reach upstream from the railroad bridge, and localized deposition was present along the right (southeast) side of the channel downstream from the bridges (fig. 33). The cross sections from these two surveys also were similar to one another except in the area between the left bank and pier 2C (figs. 30, 31). As mentioned in the previous paragraph, the frequency distribution of bed elevations were of remarkably similar shape in all three of the surveys to date at this site (fig. 28), despite the difference in discharge (table 7). The rock outcrop on the upstream left (northwest) bank showed no signs of substantial change except for minor deposition along the toe of the bank along the interface with the thalweg (fig. 33). As with all difference maps in this report, substantial deposition or scour apparent at the faces of the piers results from minor horizontal positional variances between the surveys (see the “Uncertainty Estimation” section).

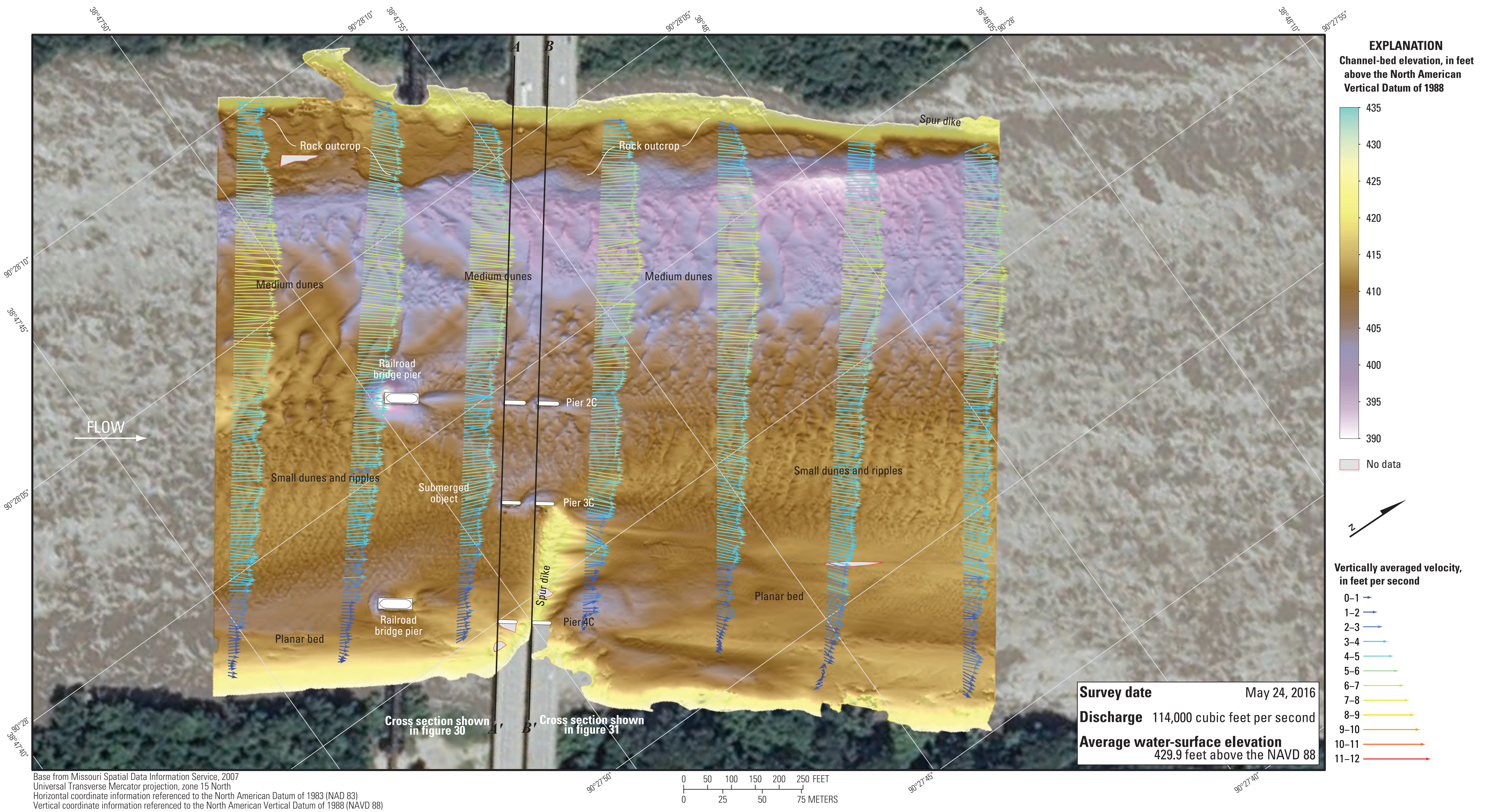


Figure 29. Bathymetry and vertically averaged velocities of the Missouri River channel near dual bridge structure A4557 on State Highway 370 near St. Louis, Missouri.

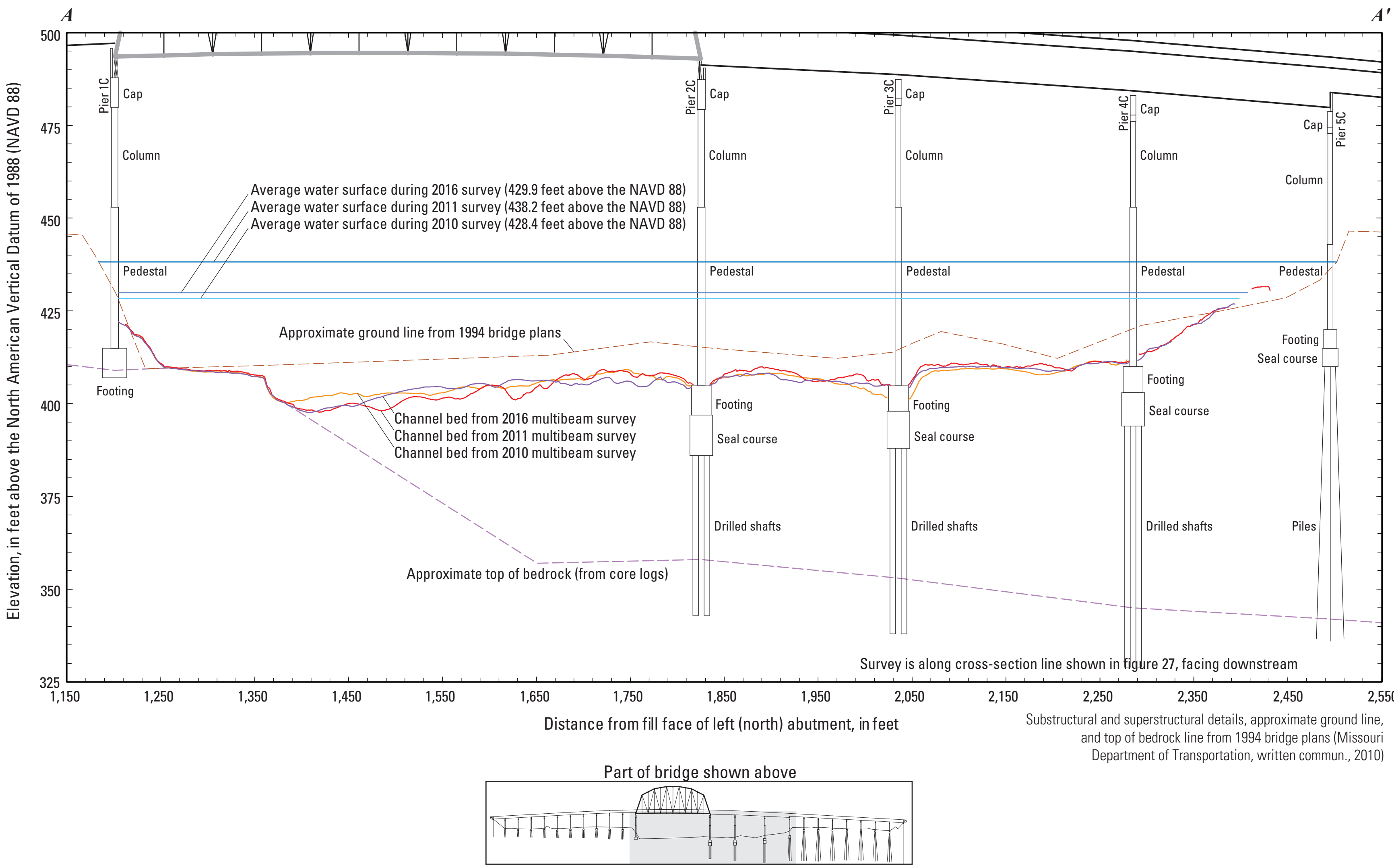


Figure 30. Key features, substructural and superstructural details, and surveyed channel bed along the upstream face of the upstream bridge of dual bridge structure A4557 on State Highway 370 crossing the Missouri River near St. Louis, Missouri.

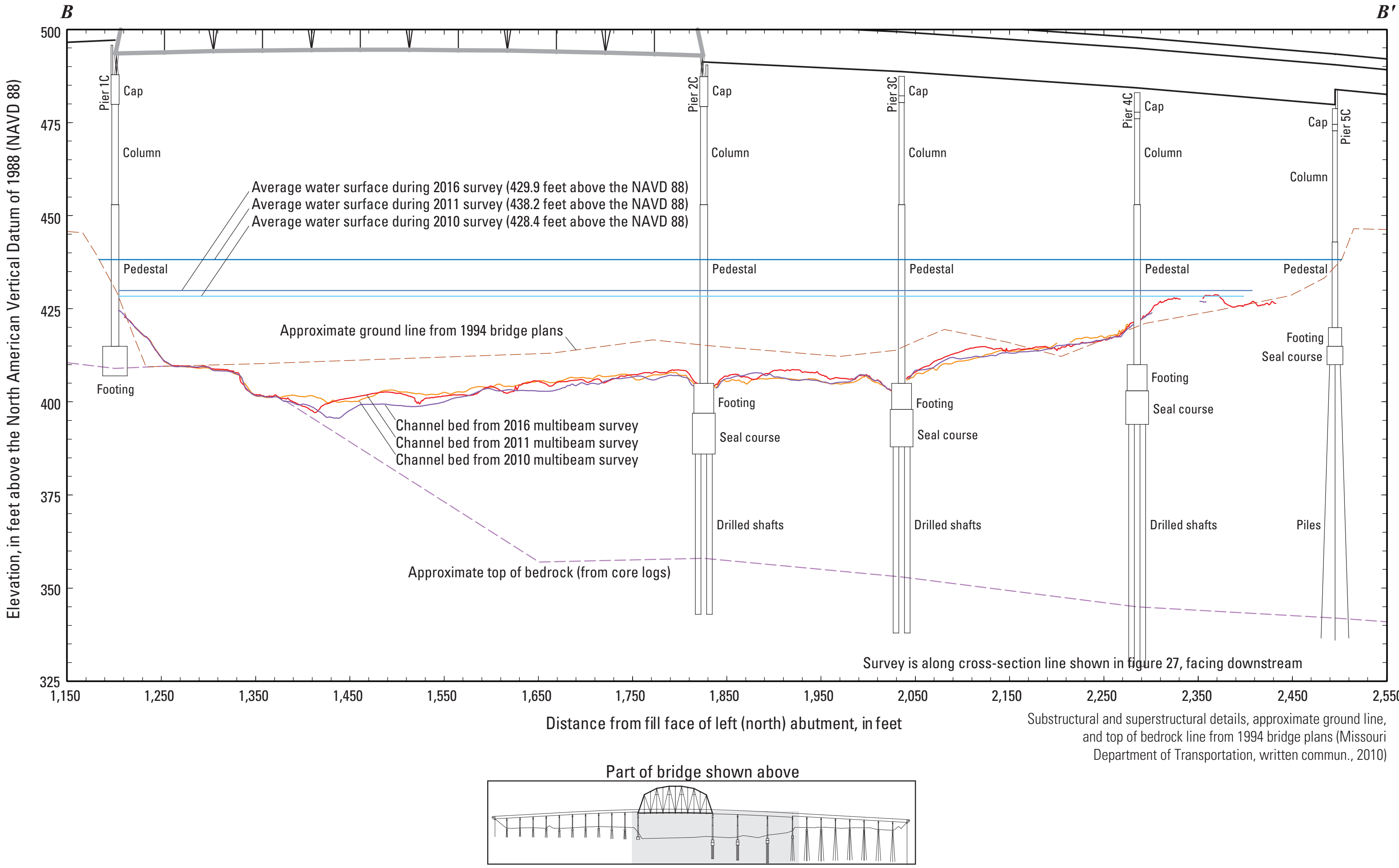


Figure 31. Key features, substructural and superstructural details, and surveyed channel bed along the upstream face of the downstream bridge of dual bridge structure A4557 on State Highway 370 crossing the Missouri River near St. Louis, Missouri.

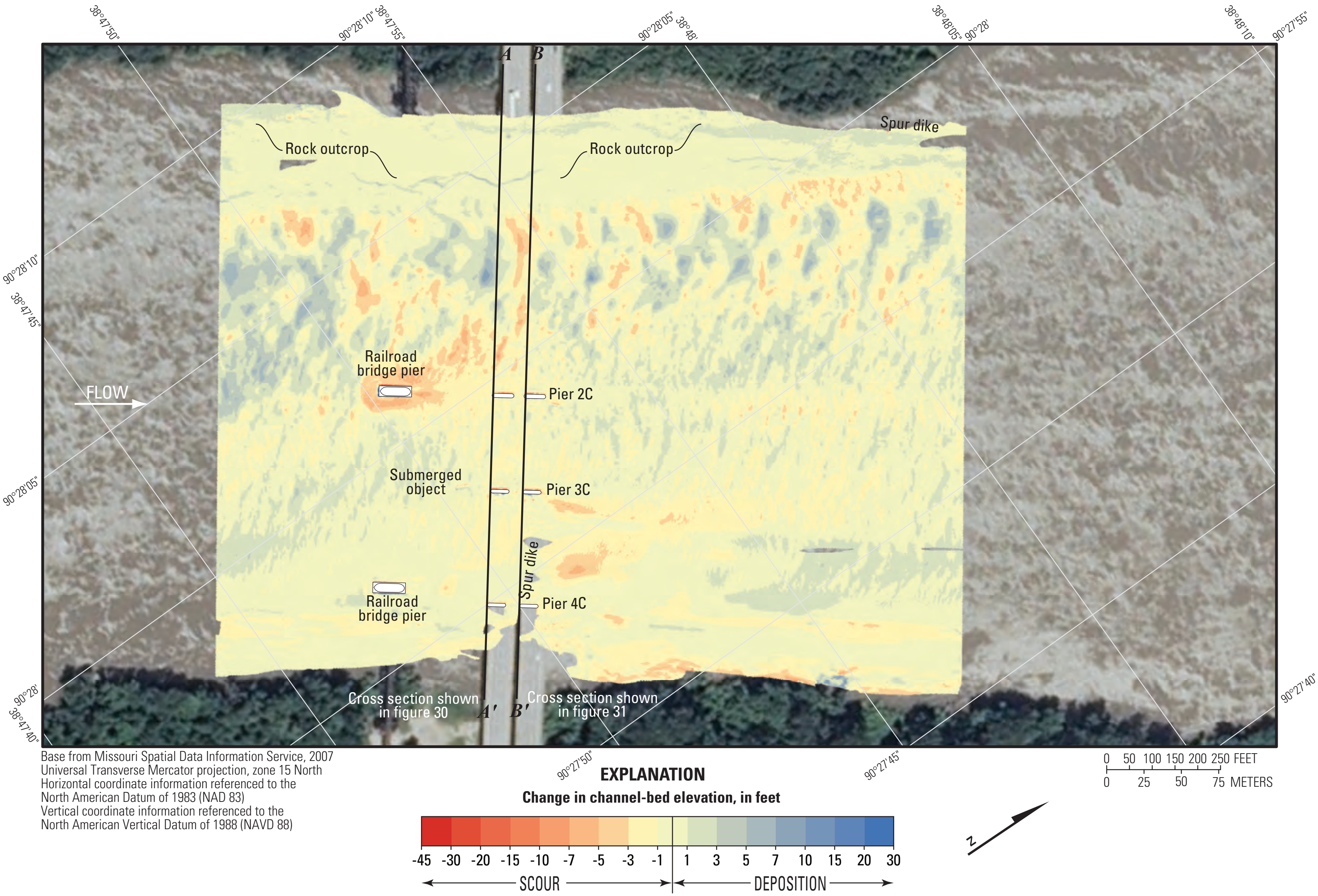


Figure 32. Difference between surfaces created from bathymetric surveys of the Missouri River channel near dual bridge structure A4557 on State Highway 370 near St. Louis, Missouri, on May 24, 2016, and August 2, 2011.

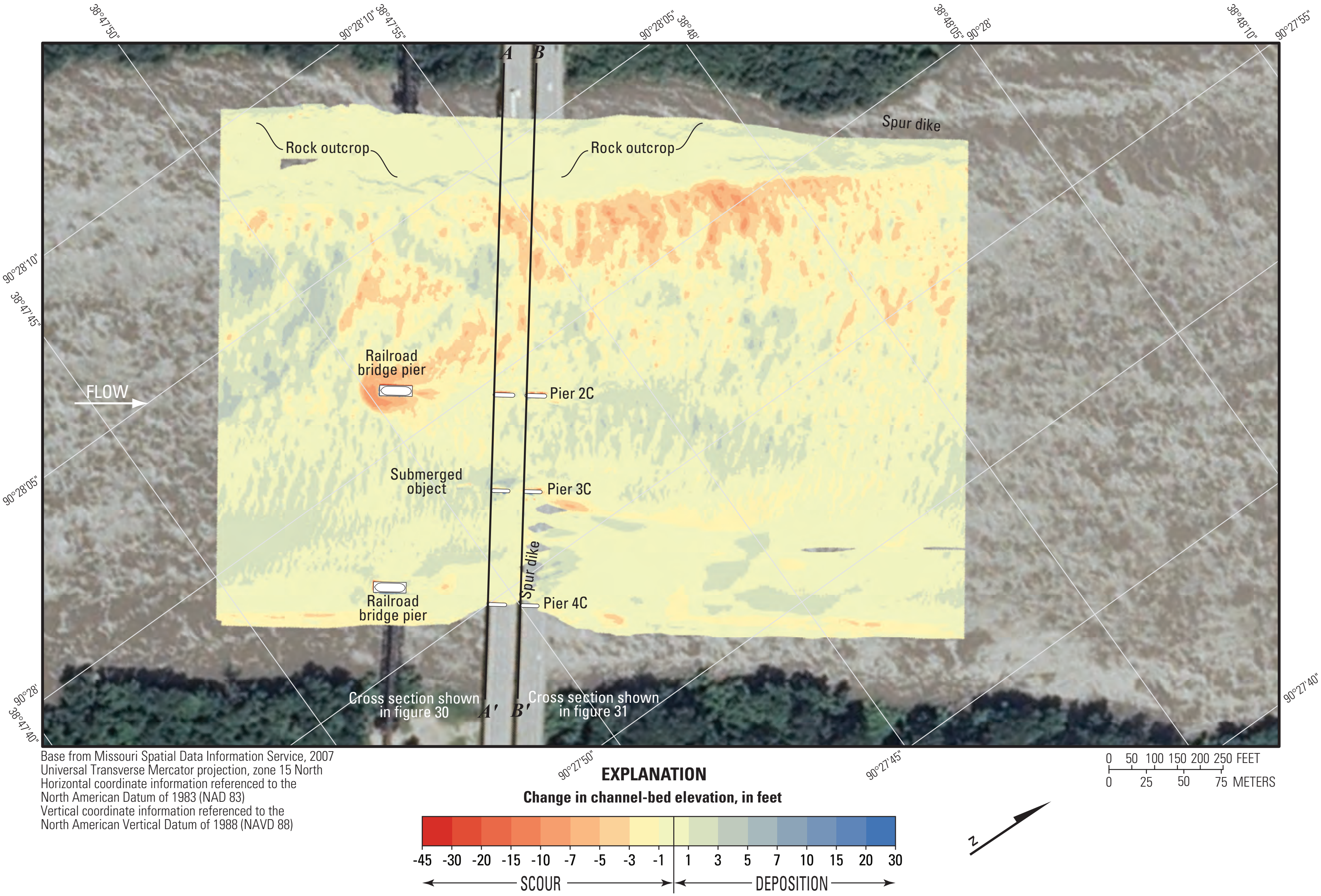


Figure 33. Difference between surfaces created from bathymetric surveys of the Missouri River channel near dual bridge structure A4557 on State Highway 370 near St. Louis, Missouri, on May 24, 2016, and October 22, 2011.

Structure A3047 on U.S. Highway 67

Structure A3047 (site 27) on U.S. Highway 67 crosses the Missouri River at RM 8.1, on the northern side of the St. Louis metropolitan area between Florissant and West Alton, Mo. (fig. 1). The site was surveyed on May 27, 2016, and the average water-surface elevation near the bridge, determined by the RTK GNSS tide solution, was 413.7 ft (table 5). Flow on the Missouri River was about 131,000 ft^3/s during the survey (table 5).

The survey area was about 1,640 ft long and about 1,350 ft wide, extending essentially from bank to bank in the main channel (fig. 34). The upstream end of the survey area was about 670 ft upstream from the centerline of structure A3047 (fig. 34). The approximate channel-bed elevations ranged from about 381 to 403 ft for most of the surveyed area (5th to 95th percentile range of the bathymetric data; table 5; fig. 35). A deep thalweg on the left (northeast) bank was about 12 to 18 ft deeper than the channel bed in the middle of the channel (fig. 34). Near the spur dike on the right (southwest) side near the bridge, deposits reached an elevation of about 404 ft, and behind the longitudinal spur dike on the left (north) side near the bridge, deposits reached an elevation of about 406 ft (fig. 34). Numerous small dunes and ripples were detected throughout the channel; a few almost-medium dune features with superimposed small dunes and ripples were present in the middle of the channel (fig. 34). As in previous surveys (Huizinga, 2011, 2012), stone revetment was present on the upstream right (southwest) bank (fig. 34).

Small to moderate scour holes were present near the main channel piers, except pier 10 near the longitudinal spur dike on the left (north) side of the channel (fig. 34). Near pier 10, the channel thalweg had an approximate minimum channel-bed elevation of about 379 ft (fig. 34; table 6), which is about 32 ft above the bottom of the seal course elevation of 346.50 ft (fig. 36; table 6); however, pier 10 is essentially embedded in the rock of a longitudinal spur dike, which will limit or prevent scour at this pier. At pier 11, the scour hole had an approximate minimum channel-bed elevation of about 375 ft, about 12 ft below the average channel bed immediately upstream from the pier (fig. 34; table 6). At pier 12, the scour hole had an approximate minimum channel-bed elevation of about 392 ft, about 6 ft below the average channel bed immediately upstream from the pier (fig. 34; table 6).

Information from bridge plans indicates that pier 10 is founded on shafts drilled 13 ft into bedrock, and about 76 ft of bed material was present between the channel thalweg and bedrock at the bridge (table 6), and about 85 ft of bed material was present between the bed at the nose of the pier and bedrock (fig. 36; difference between "Approximate elevation of scour hole at upstream pier/bent face" and "Approximate elevation of bedrock near pier/bent" in table 6). Pier 11 is founded on shafts drilled 15 ft into bedrock, and about 61 ft of bed material was present between the bottom of the scour hole and bedrock (fig. 36; table 6). Pier 12 is founded on shafts drilled 26 ft into bedrock, and about 56 ft of bed material was present between the bottom of the scour hole and bedrock (fig. 36; table 6).

Scour holes also were observed near the railroad bridge piers upstream from structure A3047. The scour hole near the railroad bridge pier upstream from pier 10 was essentially indistinguishable from the channel thalweg (fig. 34); however, substantial scour holes were present near the railroad bridge piers upstream from piers 11 and 12. Scour near the upstream railroad bridge piers did not seem to have an effect on the piers of structure A3047 (fig. 34). As in previous surveys (Huizinga, 2011, 2012), the remnant of old bridge piers were observed in the channel downstream from the existing railroad bridge piers (fig. 34).

The difference between the survey on May 27, 2016, and the previous survey on August 3, 2011 (fig. 37), indicates moderate deposition (a mean difference of +0.77 ft between the bathymetric surfaces) throughout the reach from 2011 to 2016 (table 7). The net volume of cut in the reach from 2011 to 2016 was about 34,300 yd^3, and the net volume of fill was about 91,900 yd^3, resulting in a net gain of about 57,600 yd^3 of sediment between 2011 and 2016. Substantial scour had been observed between the 2010 and 2011 surveys (Huizinga, 2012), but ongoing sediment transport processes seem to have fully replenished the sediment deposits at this site. There was an area of moderate scour near the longitudinal spur dike on the upstream left (northeast) bank (fig. 37). The cross sections from the two surveys are very similar (fig. 36), and the frequency distribution of bed elevations in 2016 was of a similar shape to that in 2011; however, a smaller percentage of survey-grid cells were at lower elevations in 2016 than 2011 (fig. 35). The cumulative percentage curves for 2016 and 2011 are remarkably similar (fig. 35). The stone revetment on the right (southwest) bank showed minor deposition in the reach upstream from the bridge (fig. 37).

The difference between the survey on May 27, 2016, and the previous nonflood survey on October 25, 2010 (fig. 38), indicates minor to moderate scour (a mean difference of –1.77 ft between the bathymetric surfaces) throughout the reach from 2010 to 2016 (table 7). The net volume of cut in the reach from 2010 to 2016 was about 117,400 yd^3, and the net volume of fill was about 13,600 yd^3, resulting in a net loss of about 103,800 yd^3 of sediment between 2010 and 2016. Most of the scour was observed in the upstream thalweg, approaching a balance of scour and deposition as one moves downstream through the reach (fig. 38). The cross sections

Structure A3047 on U.S. Highway 67.

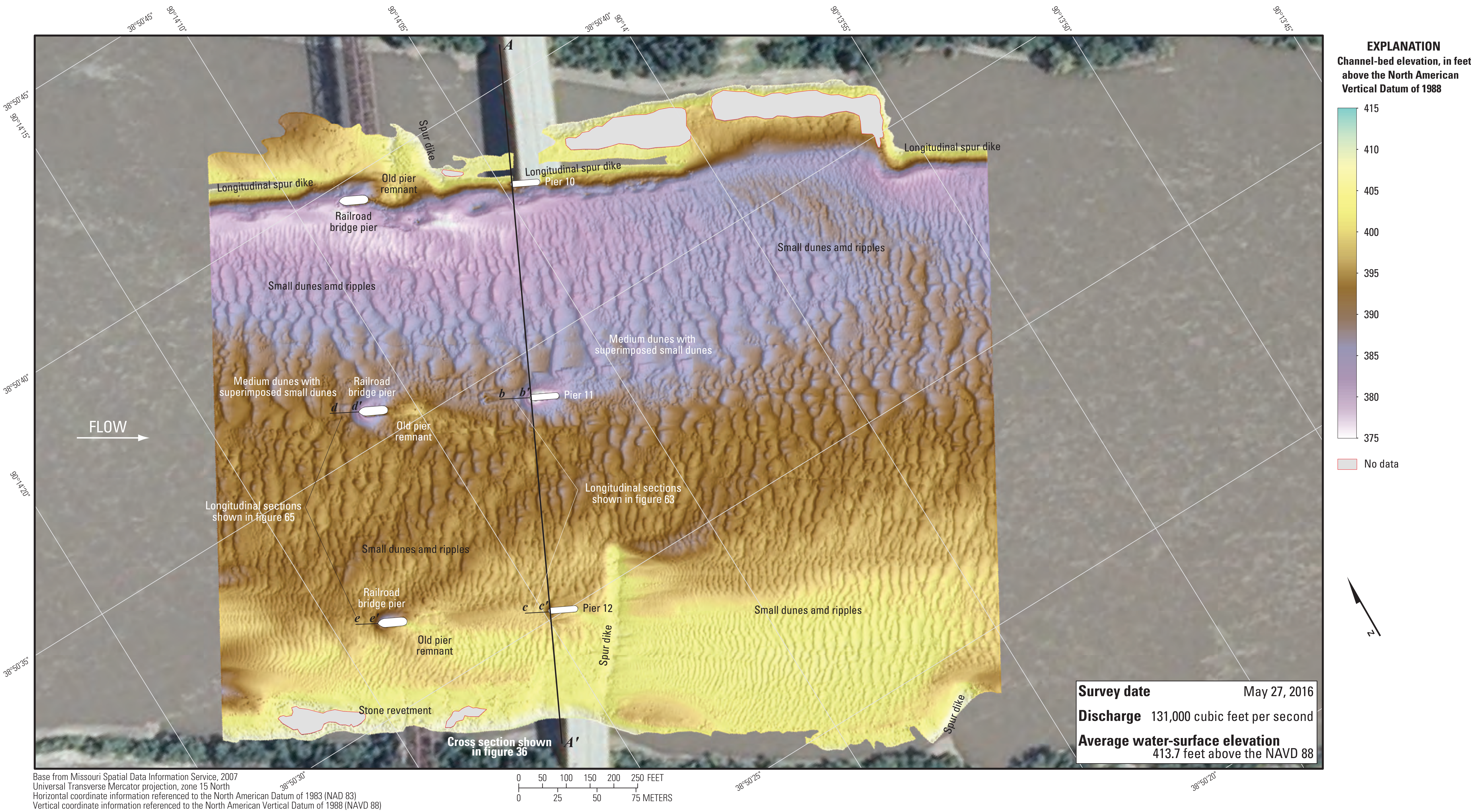


Figure 34. Bathymetric survey of the Missouri River channel near structure A3047 on U.S. Highway 67 near St. Louis, Missouri.

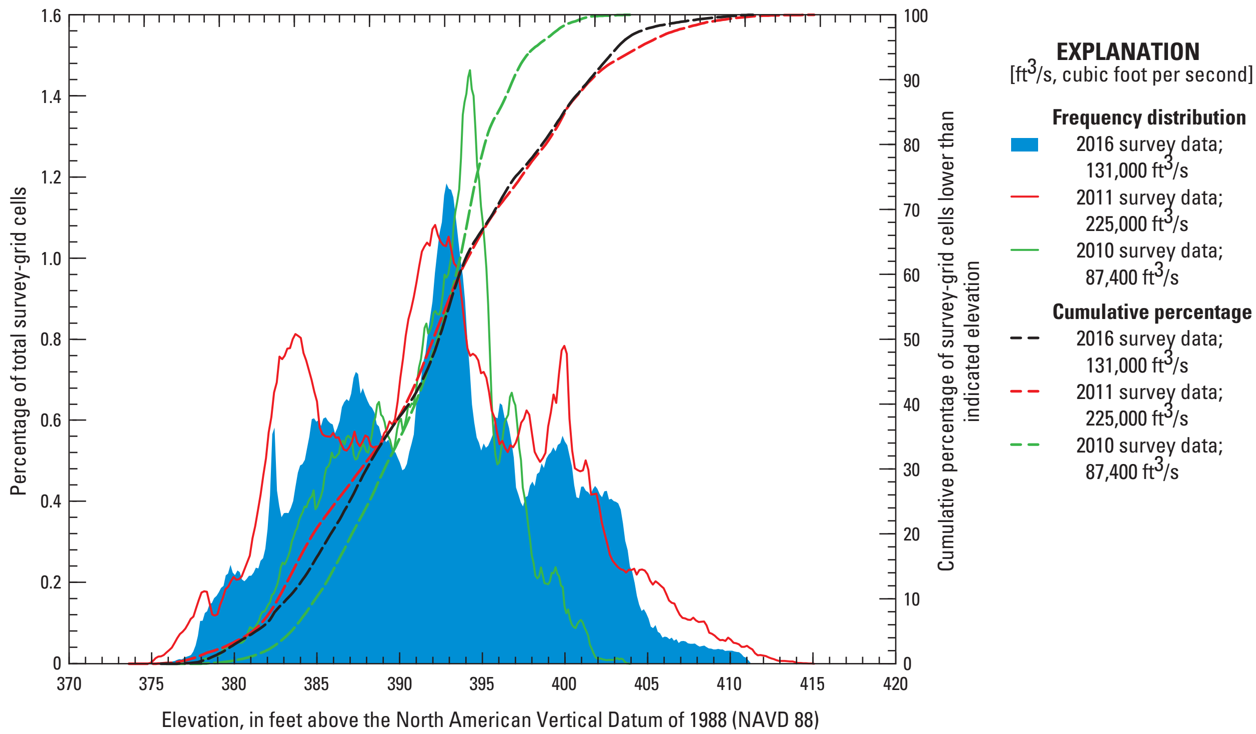


Figure 35. Frequency distribution of bed elevations for bathymetric survey-grid cells on the Missouri River near structure A3047 on U.S. Highway 67 near St. Louis, Missouri, on May 27, 2016, compared to previous surveys.

from the two surveys are similar on the left and right sides of the channel, and indicate scour for most of the channel between piers 10 and 12 (fig. 36). The frequency distribution of bed elevations was of a similar shape but wider in 2016 than in 2010; a greater percentage of survey-grid cells was at elevations above 398 ft (fig. 35).

The vertically averaged velocity vectors indicate mostly uniform flow throughout the reach, ranging from about 2 to 8 ft/s (fig. 39). Exceptions to uniform flow include angled flows near the ends of various spur dikes along the banks and minor turbulence downstream from the piers, which are slightly skewed to approach flow (fig. 39).

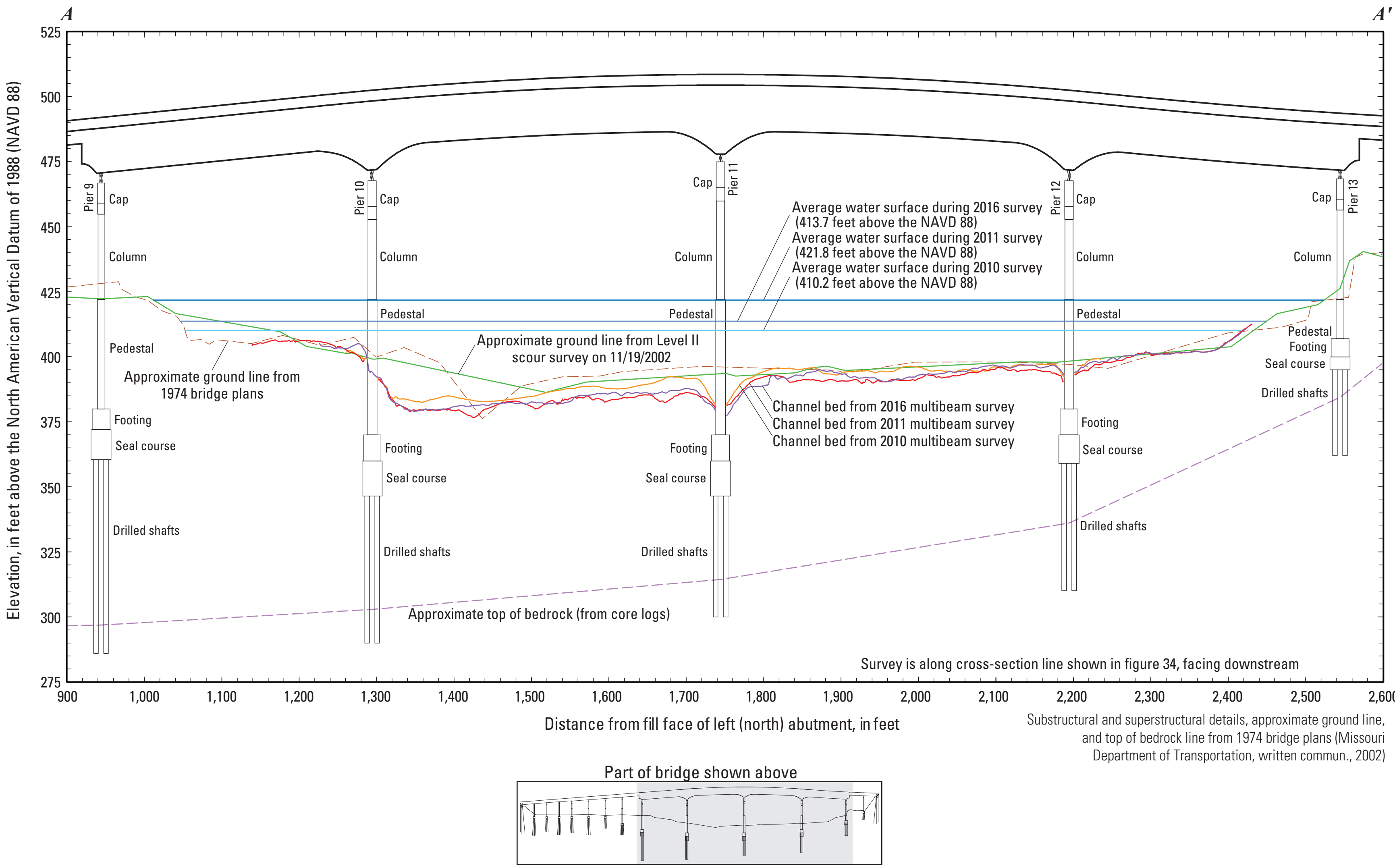


Figure 36. Key features, substructural and superstructural details, and surveyed channel bed of structure A3047 on U.S. Highway 67 crossing the Missouri River near St. Louis, Missouri.

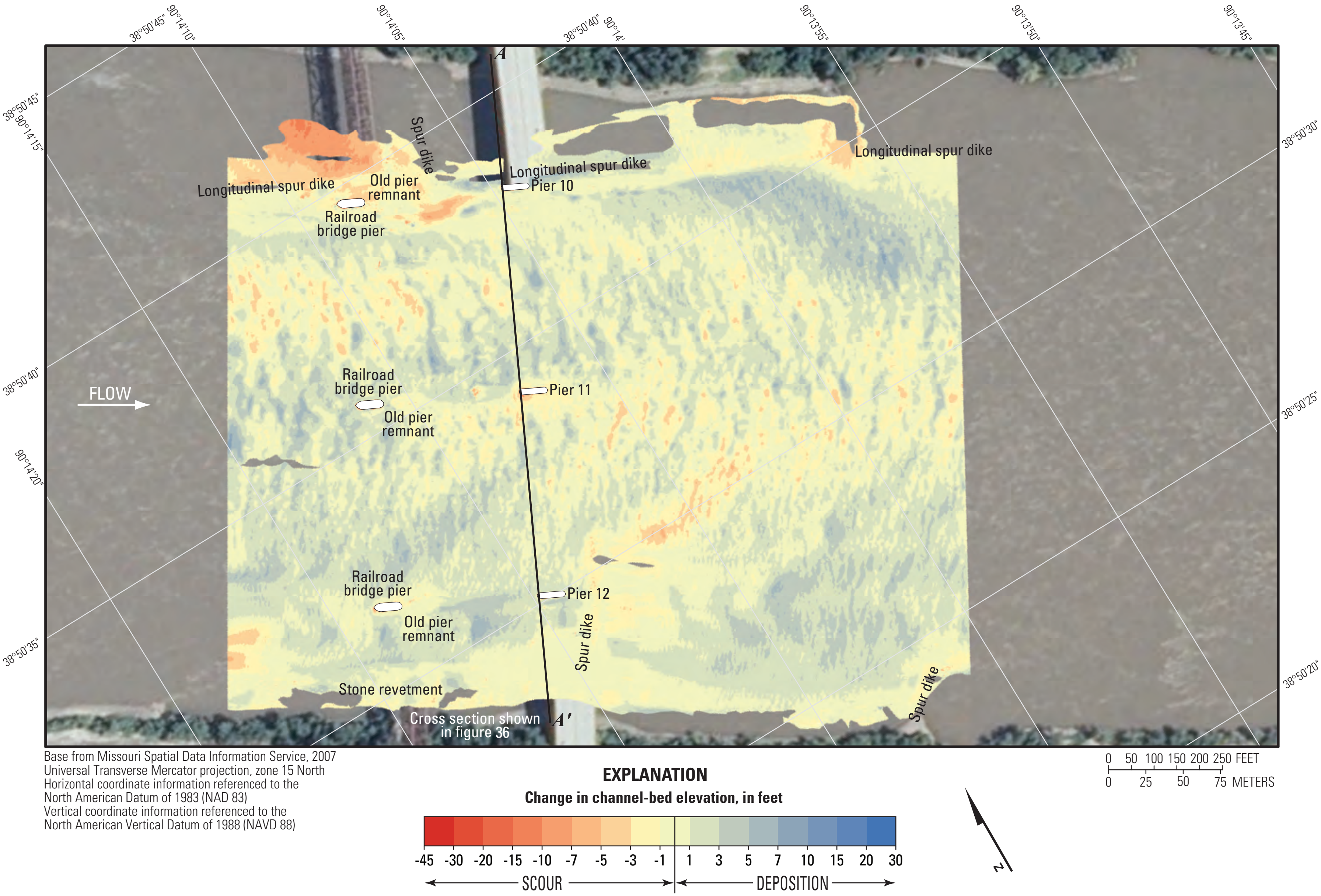


Figure 37. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A3047 on U.S. Highway 67 near St. Louis, Missouri, on May 27, 2016, and August 3, 2011.

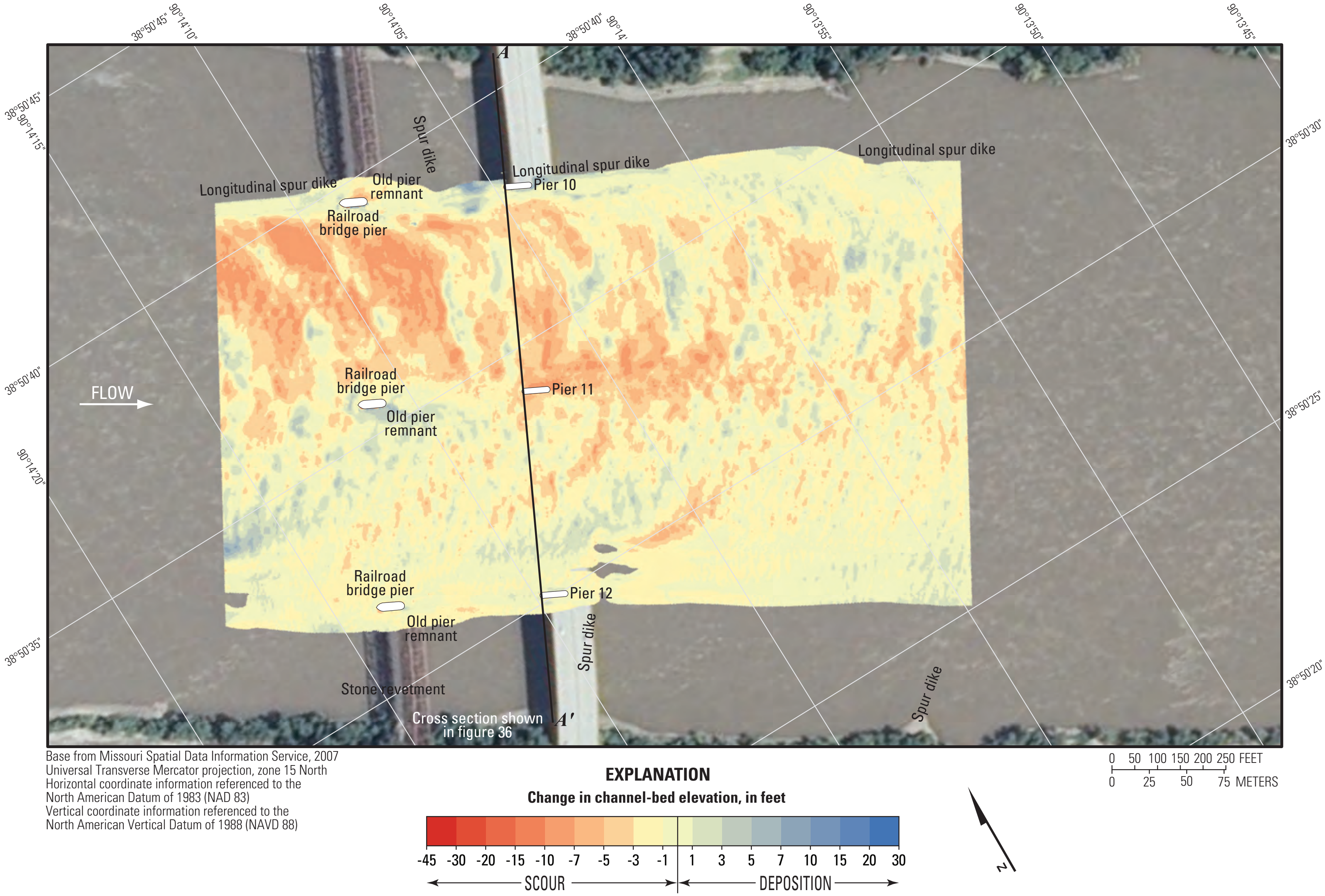


Figure 38. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A3047 on U.S. Highway 67 near St. Louis, Missouri, on May 27, 2016, and October 25, 2010.

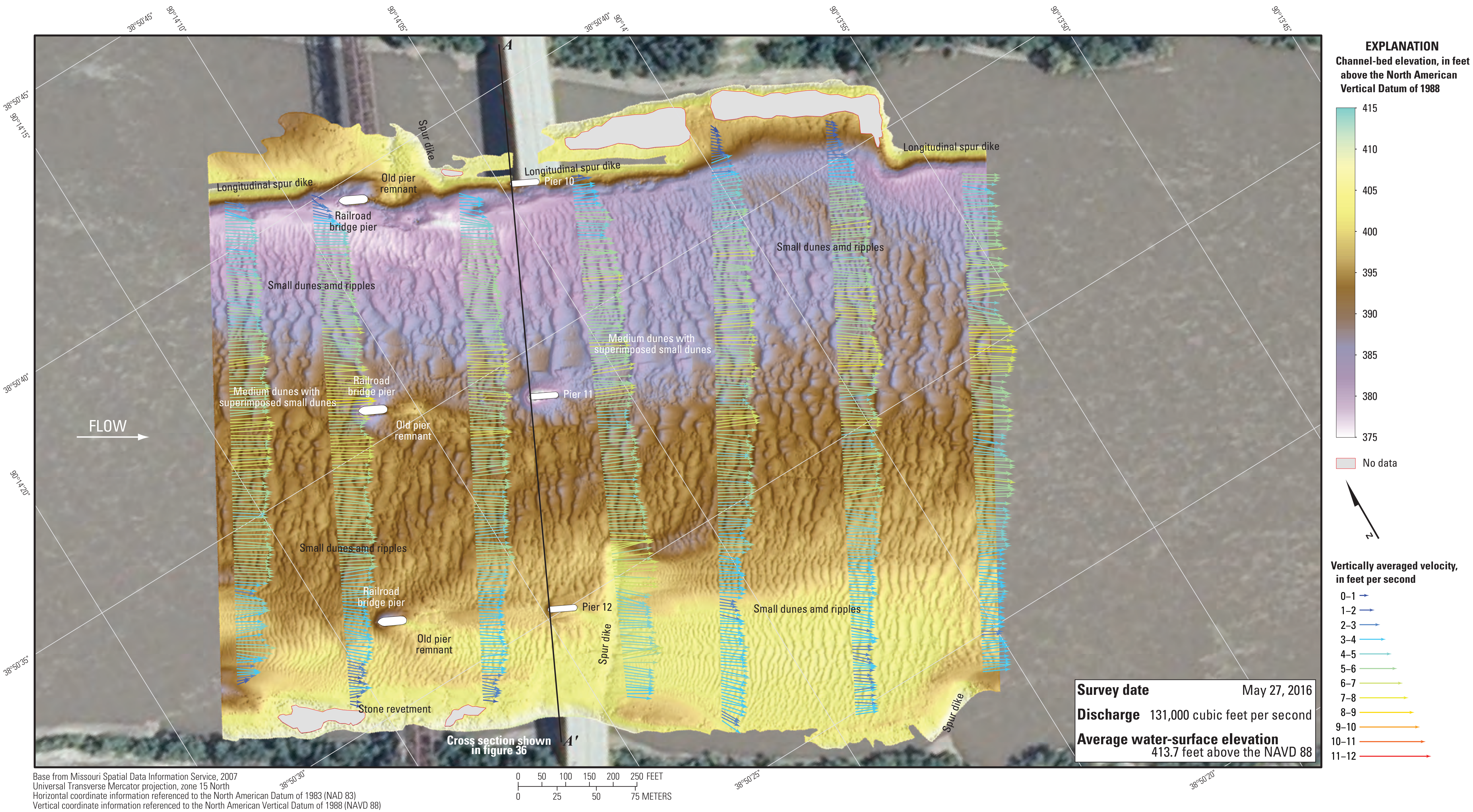


Figure 39. Bathymetry and vertically averaged velocities of the Missouri River channel near structure A3047 on U.S. Highway 67 near St. Louis, Missouri.

Structure A6500 on Interstate 70

Structure A6500 (site 33) on Interstate 70 crosses the Mississippi River at RM 181.2, on the eastern side of St. Louis City, Mo., just north of downtown (fig. 1). The site was surveyed on May 25, 2016, and the average water-surface elevation near the bridge, determined by the RTK GNSS tide solution, was 396.6 ft (table 5). Flow on the Mississippi River was about 276,000 ft^3/s during the survey (table 5).

The survey area was about 1,970 ft long and about 1,480 ft wide, extending from bank to bank in the main channel (fig. 40). The upstream end of the survey area was about 860 ft upstream from the centerline of structure A6500 (fig. 40). The approximate channel-bed elevations ranged from about 354 to 383 ft for most of the surveyed area (5th to 95th percentile range of the bathymetric data; table 5; fig. 41), except downstream from the right (west) main channel pier, where the overall minimum channel-bed elevation was 334 ft (tables 5, 8; fig. 40). A poorly defined thalweg was present along the left (east) bank throughout the surveyed area. Numerous small dunes and ripples were detected throughout the channel, and a few medium dune features with superimposed small dunes and ripples were present in the middle of the channel (fig. 40). As in the previous survey (Huizinga and others, 2010), stone revetment was present on both banks throughout the reach (fig. 40).

There was no scour hole near left (east) main channel pier 12 because the pier is surrounded with a riprap blanket (figs. 40, 42; table 8). The top of the riprap blanket is slightly higher than the bottom of the pier seal course elevation of 361.5 ft (fig. 42; table 8). Main channel pier 11 seems to be partly surrounded with mounded riprap, but the top of the riprap pile is below the bottom of the seal course elevation on the downstream side of the pier (fig. 40; table 8). The approximate elevation of the bottom of the scour hole on the upstream side of the pier is about 348 ft, about 13 ft below the bottom of the seal course (table 8). Information from bridge plans indicates that pier 11 is founded on shafts drilled 22 ft into bedrock, and about 15 ft of bed material was present between the bottom of the scour hole and bedrock (fig. 42; table 8). The undermined seal course is evident in a point cloud image of the right (west) side of pier 11 (fig. 43); furthermore, the seal course seems to be larger than the footing by about 7 ft on each side (fig. 43), which is not indicated in the plans (fig. 42). This is true for both piers (appendix 1, fig. 1–6). The approximate ground line from the 2010 bridge plans was digitized directly from the

Structure A6500 on Interstate 70.

Figure 40. Bathymetric survey of the Mississippi River channel near structure A6500 on Interstate 70 in St. Louis, Missouri.

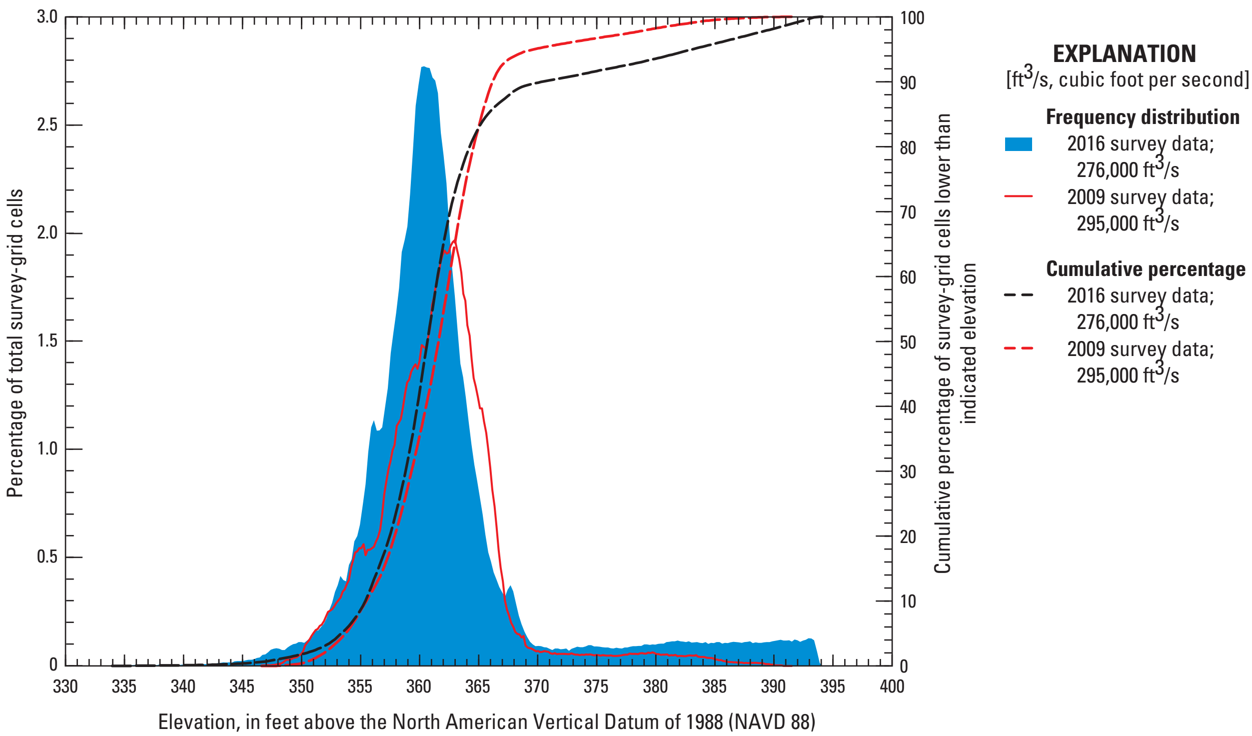


Figure 41. Frequency distribution of bed elevations for bathymetric survey-grid cells on the Mississippi River near structure A6500 on Interstate 70 in St. Louis, Missouri, on May 25, 2016, compared to previous surveys.

plans and seems to plot in the correct location relative to the interface between the footings and seal courses according to the plans; however, it is uncertain why this line is more than 20 ft higher than the two bathymetric survey lines (fig. 42).

This site was the subject of a preconstruction habitat assessment, using data collected with the MBMS (Huizinga and others, 2010). The previous survey gives unique insight into the effects of the construction of structure A6500 on the channel in this reach. The difference between the survey on May 25, 2016, and the preconstruction survey on July 7, 2009 (fig. 44), indicates moderate scour (a mean difference of –1.36 ft between the bathymetric surfaces) overall in the reach from 2009 to 2016 (table 7). The net volume of cut in the reach from 2009 to 2016 was about 336,500 yd^3, and the net volume of fill was about 166,900 yd^3, resulting in a net loss of about 169,600 yd^3 of sediment between 2009 and 2016. Large areas of substantial deposition of more than 10 ft were upstream from the bridge and in the middle of the channel downstream from the bridge, as well as along the right (west) bank downstream from the bridge (fig. 44); however, there was substantial scour along the left (east) bank throughout the reach and substantial scour of nearly 30 ft at and downstream from pier 11 (fig. 44). The cross sections from the two surveys show this trend as well; the 2016 survey alternates from being above and below the 2009 survey section (fig. 42). The frequency distribution of bed elevations was of a similar shape in 2016 compared to 2009 but with a higher percentage of survey-grid cells at a slightly lower elevation than in 2009, which mirrors the observed scour in the reach (fig. 41). The discharges and water-surface elevations for the 2009 and 2016 surveys were similar (table 7; fig. 42).

In the preconstruction survey in 2009, flow was observed to cross from the Illinois (east) side of the river to the Missouri (west) side through the reach, and generally this was reflected in the vertically averaged velocity vectors for the present (2016) survey (fig. 45). Both piers are skewed to approach flow, and the scour hole near pier 11 has the typical characteristics of a hole at a skewed pier, being longer on the side with impinging flow and an angled line of deposition on the leeward side (figs. 40, 45); however, the 55-ft-wide, square nose of pier 11, a mild constriction downstream from the pier, and the additional scour from adjacent mooring dolphins downstream likely have exacerbated the scour on the leeward side of the pier by increasing local turbulence and pulling sediment into suspension (figs. 40, 45). A similar situation was observed at the main channel pylon for structure A7650 in Kansas City in 2015 (Huizinga, 2016, fig. 24).

The vertically averaged velocity vectors indicate mostly uniform flow throughout the reach, ranging from about 2 to 8 ft/s (fig. 45). Exceptions to uniform flow include moderate turbulence and flow reversal downstream from the piers which are skewed to approach flow, and mild turbulence near the various mooring dolphins in the reach (fig. 45).

Table 8. Results near piers and bents from surveys on the Mississippi River near St. Louis, Missouri, May 23–27, 2016.

[MoDOT, Missouri Department of Transportation; ft, feet; —, not known/applicable; all elevations are in feet above the North American Vertical Datum of 1988]

Site number (fig. 1)	MoDOT structure number	MoDOT pier/bent number	Foundation information				Approximate minimum channel-bed elevation in scour hole near pier/bent[a] (ft)	Approximate elevation of scour hole at upstream pier/bent face (ft)	Approximate elevation of bedrock near pier/bent (ft)	Approximate distance between bottom of scour hole and bedrock (ft)	Depth of scour hole from upstream channel bed (ft)	Approximate frontal slope of scour hole (ft/ft)
			Type	Width (ft)	Penetration into bedrock (ft)	Bottom of seal course elevation (ft)						
33	A6500	12	Drilled shaft	55	18	361.50	[b,c]350	[b]362	304	46	([b])	([b])
		11	Drilled shaft	55	22	361.50	334	348	318	15	19	1.97
34	A1500	5	Drilled shaft	27	7	356.00	358	379	287	71	3	([d])
		4	Drilled shaft	28	7	339.00	340	340	297	43	14	1.85
		3	Drilled shaft	30	7	347.00	352	352	324	28	12	1.87
		2	Footing	16	1	—	361	383	356	5	([d])	([d])
35	A4936	7	Piling	28	1	361.00	373	374	294	79	12	1.79
		8	Piling	36	1	353.00	360	360	297	63	11	1.57
		9	Piling	36	1	353.00	357	357	297	60	10	1.79
		10	Piling	36	1	348.00	360	364	294	66	2	([e])
		11	Piling	36	1	344.00	356	360	293	63	2	([e])
		[f]12	Piling	56	1	328.00	349	351	295	56	6	1.28
	A1850	7	Piling	28	1	361.00	374	374	294	80	[g]2	([g])
		8	Piling	36	1	353.00	368	368	297	71	[g]6	2.27
		9	Piling	36	1	353.00	357	357	297	60	10	1.75
		10	Piling	36	1	348.00	353	363	294	59	0	([e])
		11	Piling	36	1	344.00	352	358	293	59	1	([e])

[a]The point of lowest elevation in the scour hole near the bridge pier/bent, not necessarily at the upstream face.

[b]Pier/bent is surrounded by a substantial riprap blanket.

[c]Indicated elevation is the minimum elevation in the in area immediately adjacent to the riprap blanket around the pier/bent.

[d]Scour hole is substantially affected by stone revetment along the bank.

[e]Poorly defined scour hole at this pier/bent.

[f]Pier 12 is a single continuous pier that extends between structures A4936 and A1850; therefore, results shown for this pier are the same for both structures.

[g]Scour hole at this pier/bent is substantially affected by upstream pier/bent.

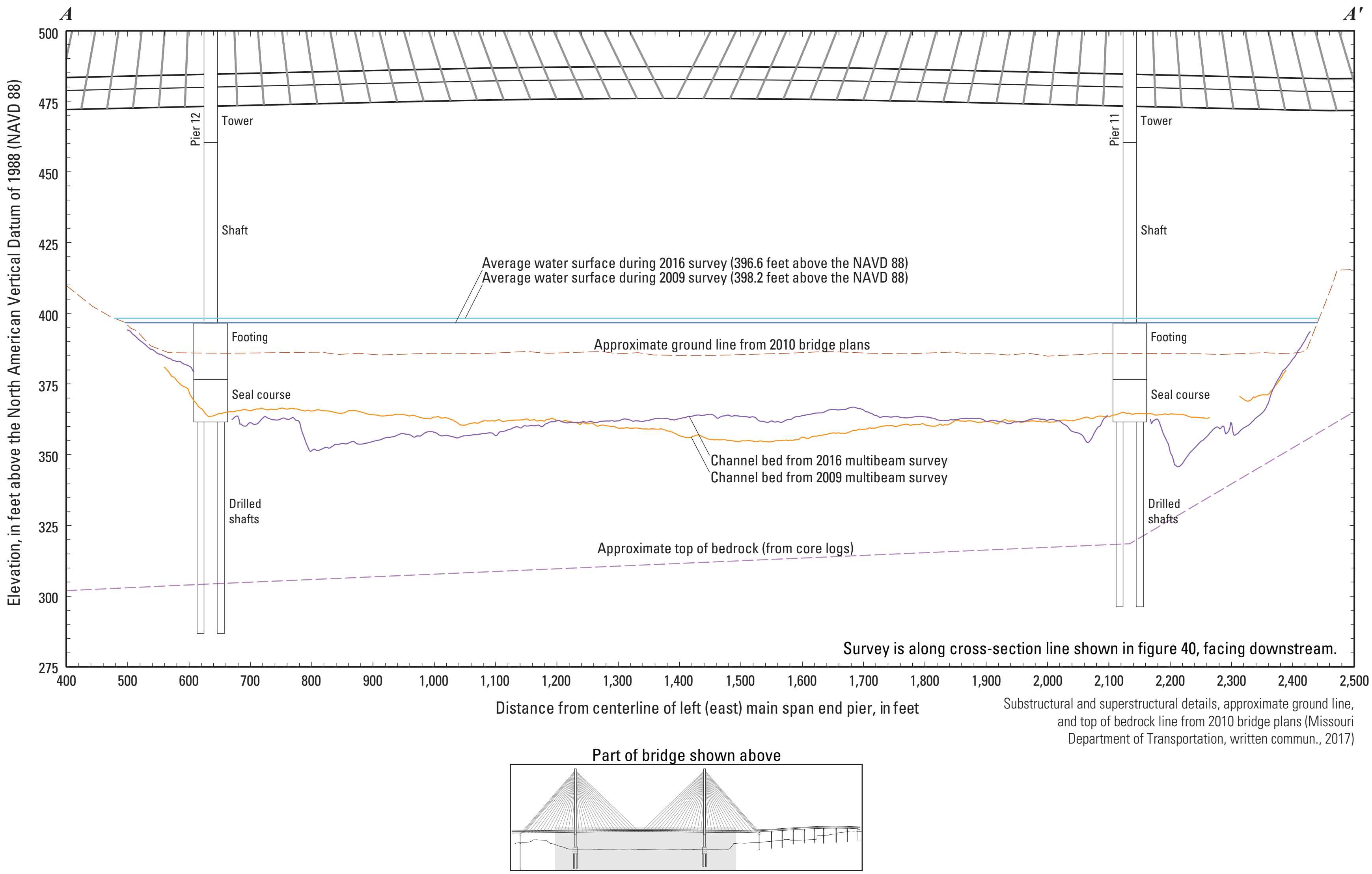


Figure 42. Key features, substructural and superstructural details, and surveyed channel bed of structure A6500 on Interstate 70 crossing the Mississippi River in St. Louis, Missouri.

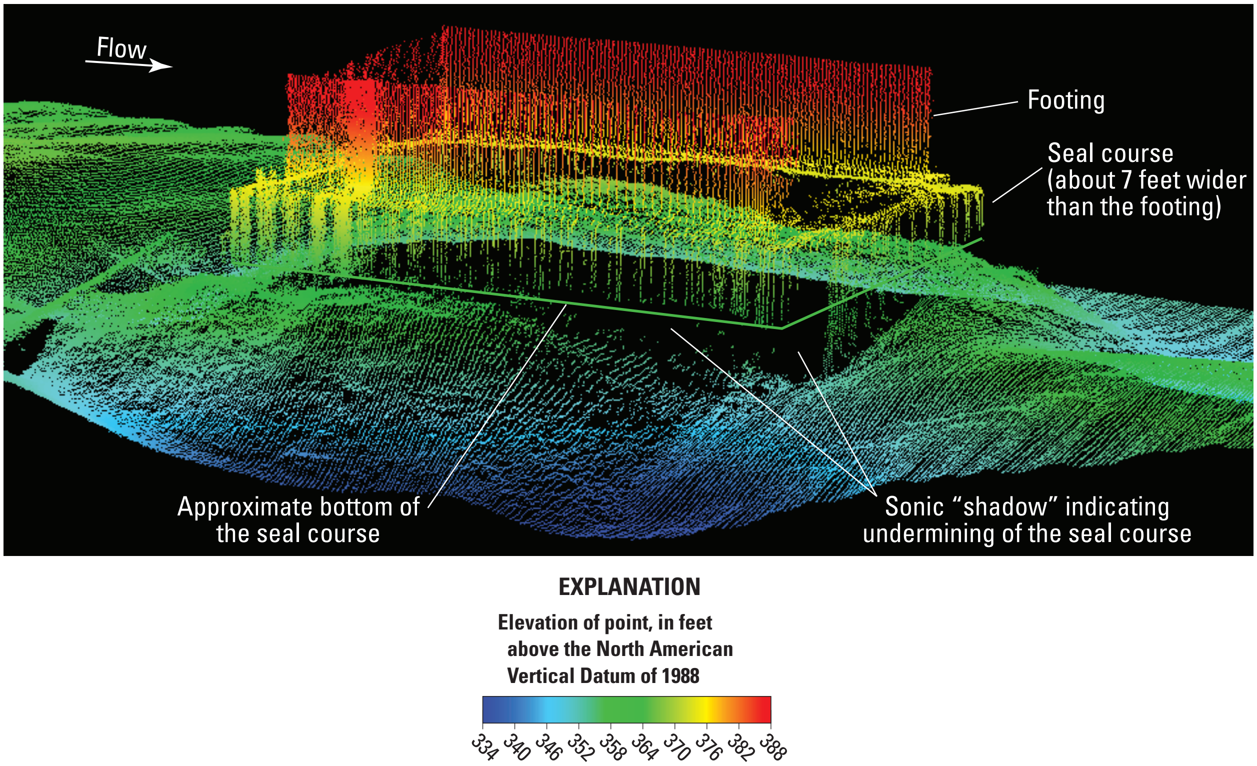


Figure 43. Point cloud visualization of the channel bed and right (west) side of main channel pier 11 of structure A6500 on Interstate 70 crossing the Mississippi River in St. Louis, Missouri.

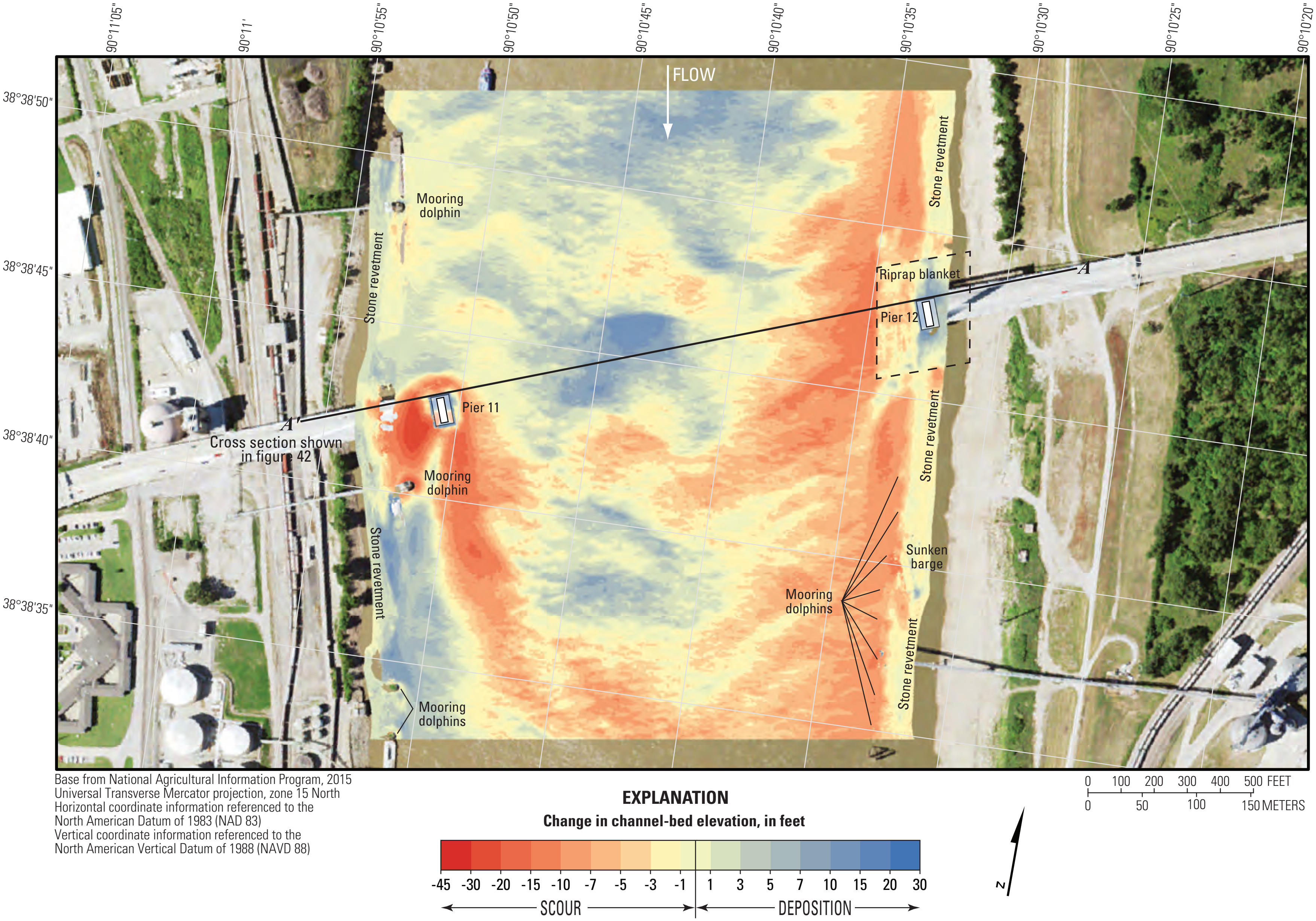


Figure 44. Difference between surfaces created from bathymetric surveys of the Mississippi River channel near structure A6500 on Interstate 70 in St. Louis, Missouri, on May 25, 2016, and before construction, on July 7, 2009.

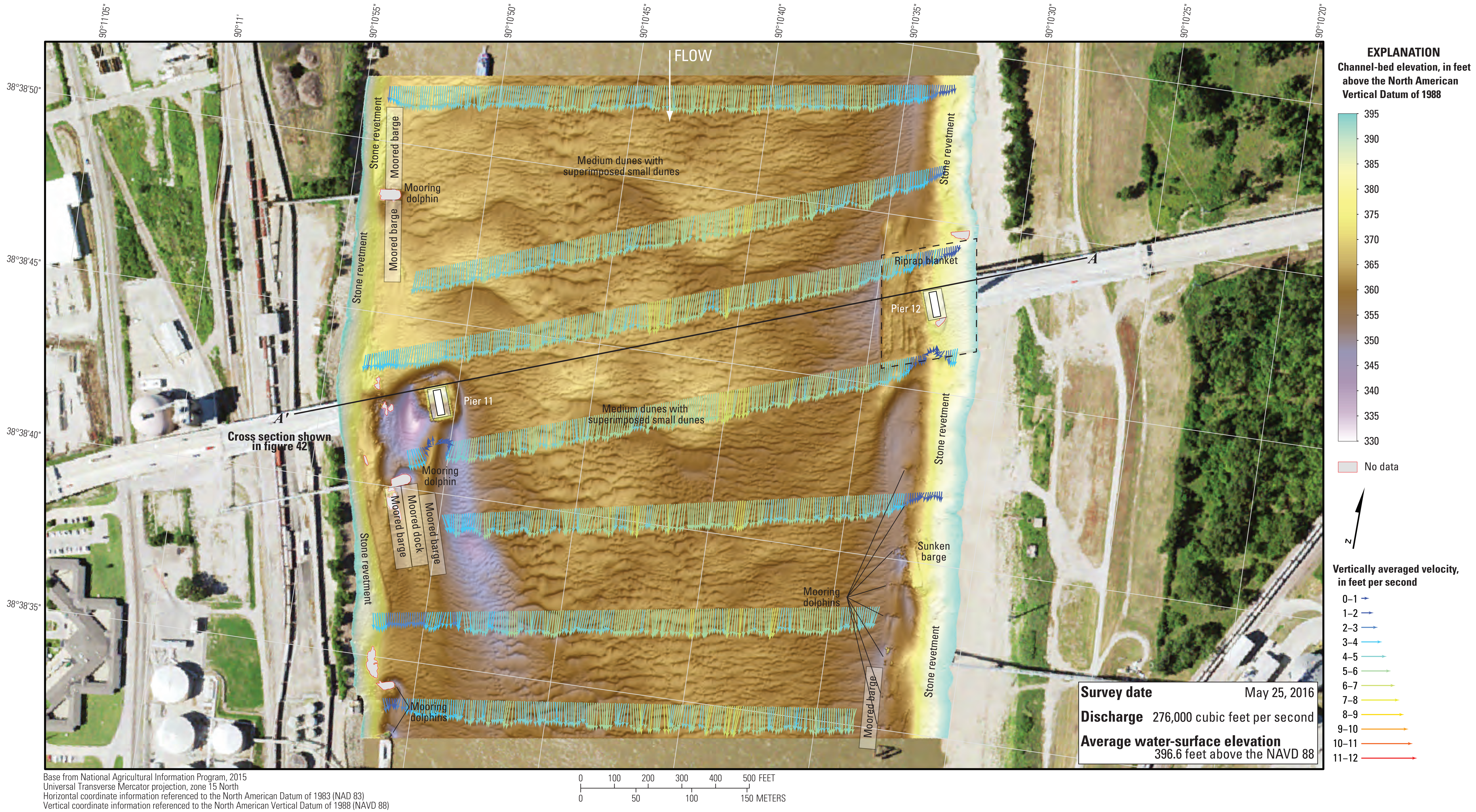


Figure 45. Bathymetry and vertically averaged velocities of the Mississippi River channel near structure A6500 on Interstate 70 in St. Louis, Missouri.

Structure A1500 on Interstate 55

Structure A1500 (site 34) on Interstate 55 crosses the Mississippi River at RM 179.2 on the eastern side St. Louis City, Mo., just east of downtown (fig. 1). The site was surveyed on May 25, 2016, and the average water-surface elevation near the bridge, determined by the RTK GNSS tide solution, was 395.7 ft (table 5). Flow on the Mississippi River was about 279,000 ft^3/s during the survey (table 5).

The survey area was about 1,640 ft long and about 1,710 ft wide, extending from bank to bank in the main channel (fig. 46). The upstream end of the survey area was about 720 ft upstream from the centerline between structure A1500 (fig. 46). The approximate channel-bed elevations ranged from about 350 to 382 ft for most of the surveyed area (5th to 95th percentile range of the bathymetric data; table 5; fig. 47), except near pier 4 of structure A1500 and along the toe of the left (east) bank (fig. 46). A deep thalweg was along the left (east) bank throughout the surveyed reach and was about 12 to 18 ft deeper than the channel bed in the middle of the channel (fig. 46). A row of medium dune features with superimposed small dunes and ripples were observed in the right (west) side of the channel, along with numerous small dunes and ripples throughout the rest of the channel (fig. 46). As in the previous survey (Huizinga, 2011), the stone revetment was present on both banks (fig. 46).

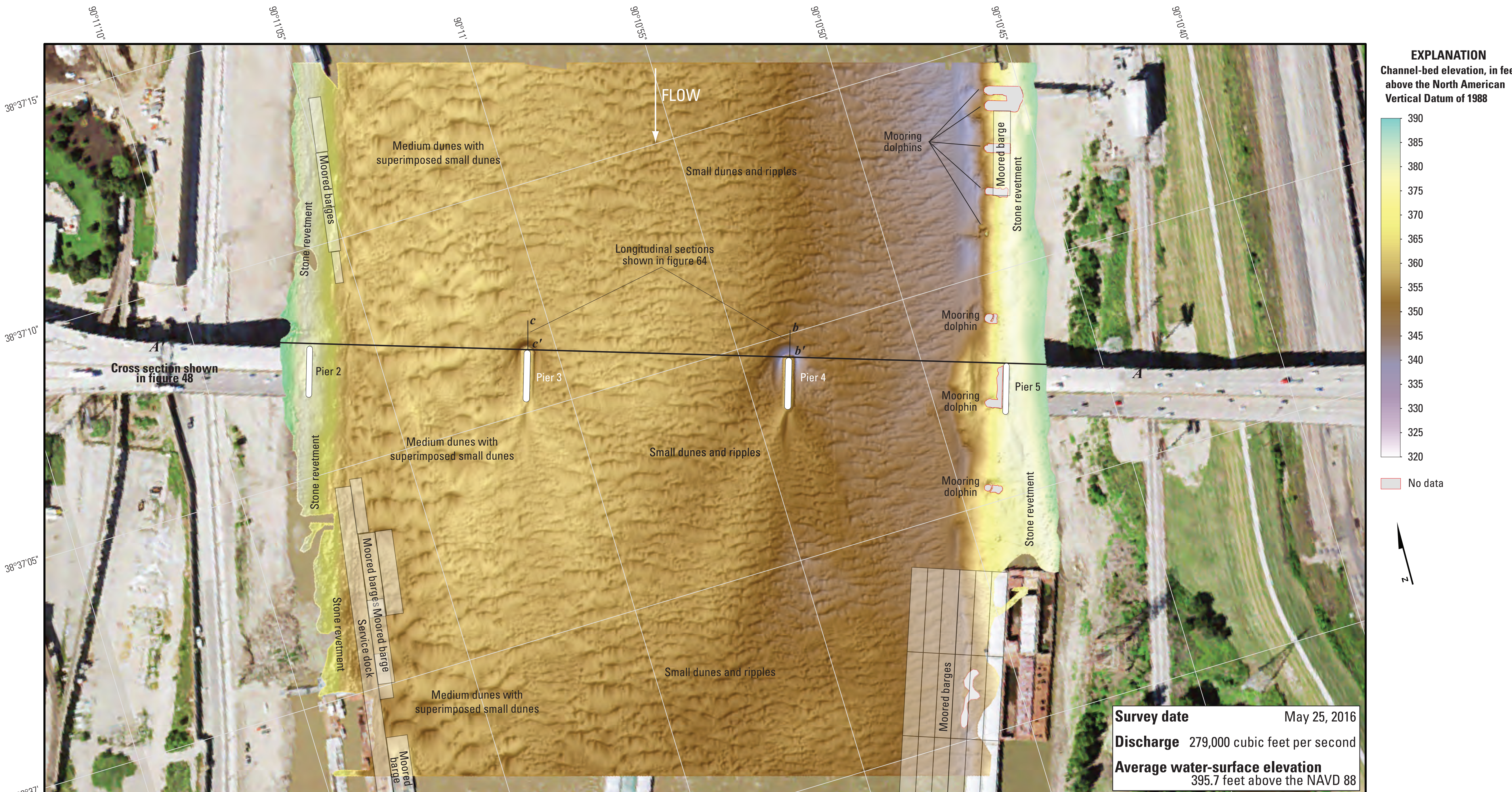
There was no observed scour hole near the left bank pier (pier 5, fig. 46). The upper left bank is covered with gravel and cobble-sized revetment that seems to extend to the toe of the bank and will limit or prevent scour at this pier. The channel thalweg at the toe of the left bank had a minimum elevation of about 350 ft immediately downstream from pier 5 (fig. 46), which is about 6 ft below the bottom of the seal course elevation of 356.00 ft (fig. 48; table 8); however, the thalweg is more than 100 ft to the right from the pier (figs. 46, 48). Information from bridge plans indicates that pier 5 is founded on shafts drilled 7 ft into bedrock, and about 63 ft of bed material was present between the channel thalweg and bedrock near the bridge (fig. 48), and about 71 ft of bed material was present between the bed and bedrock at the upstream pier face (fig. 48; table 8).

A moderate scour hole was present near the left main channel pier (pier 4, fig. 46) with a minimum elevation of about 340 ft, about 14 ft below the average channel bed immediately upstream from the pier (fig. 46; table 8), and only about 1 ft above the bottom of the seal course elevation (fig. 48; table 8). Information from bridge plans indicates that pier 4 is founded on shafts drilled 7 ft into bedrock, and about 43 ft of bed material was present between the bottom of the scour hole and bedrock (fig. 48; table 8). Similarly, a moderate scour hole was present near the right main channel pier (pier 3, fig. 46) with a minimum elevation of about 352 ft, about 12 ft below the average channel bed immediately upstream from the pier (fig. 46; table 8), and about 5 ft above the bottom of the seal course elevation (fig. 48; table 8). Information from bridge plans indicates that pier 3 also is founded on shafts drilled 7 ft into bedrock, and about 28 ft of bed material was present between the bottom of the scour hole and bedrock (fig. 48; table 8).

As with the left bank pier, there was no observable scour hole at the right bank pier (pier 2, fig. 46). The right bank is covered with granite paving stone revetment under the bridge and upstream that extends to the toe of the bank and will limit or prevent scour at this pier. The minimum elevation at the toe of the right bank near pier 2 was about 361 ft (fig. 46), which is about 5 ft above the bottom of the footing elevation of 355.63 ft (fig. 48); however, the toe of the bank is nearly 90 ft to the left from the pier (figs. 46, 48). Information from bridge plans indicates that pier 2 is founded on footings on bedrock, and about 27 ft of bed material were present between the bed and bedrock at the nose of the pier (fig. 48; difference between "Approximate elevation of scour hole at upstream pier/bent face" and "Approximate elevation of bedrock near pier/bent" in table 8).

The difference between the survey on May 25, 2016, and the previous survey on October 20, 2010 (fig. 49), indicates a balance of scour and deposition (a mean difference of –0.38 ft between the bathymetric surfaces) throughout the reach from 2010 to 2016 (table 7). The net volume of cut in the reach from 2010 to 2016 was about 141,500 yd^3, and the net volume of fill was about 105,700 yd^3, resulting in a net loss of about 35,800 yd^3 of sediment between 2010 and 2016. There was moderate deposition of more than 10 ft in the middle of the channel downstream from the bridge (fig. 49); however, substantial scour of as much as 10 ft was observed in the middle of the upstream channel, and moderate scour was observed along the left (east) side of the channel throughout the reach (fig. 49). The cross section from the 2016 survey alternates above and below the 2010 survey; however, the scour holes at piers 3 and 4 are similar in size and depth (fig. 48). The

Structure A1500 on Interstate 55.



Base from National Agricultural Information Program, 2015
Universal Transverse Mercator projection, zone 15 North
Horizontal coordinate information referenced to the North American Datum of 1983 (NAD 83)
Vertical coordinate information referenced to the North American Vertical Datum of 1988 (NAVD 88)

Figure 46. Bathymetric survey of the Mississippi River channel near structure A1500 on Interstate 55 in St. Louis, Missouri.

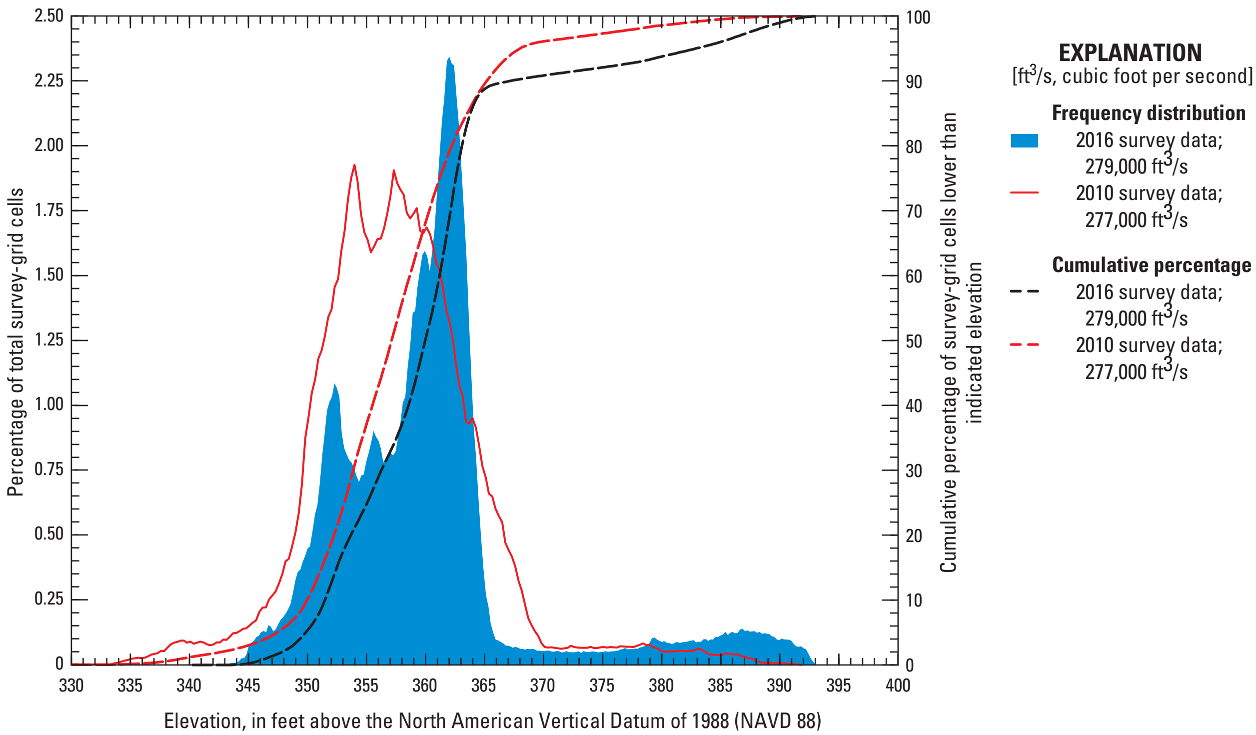


Figure 47. Frequency distribution of bed elevations for bathymetric survey-grid cells on the Mississippi River near structure A1500 on Interstate 55 in St. Louis, Missouri, on May 25, 2016, compared to previous surveys.

discharges of the Mississippi River were similar for both surveys (table 7); however, the frequency distribution of bed elevations was substantially narrower in 2016 than in 2010 because of a higher minimum channel-bed elevation and a higher percentage of survey-grid cells at elevations from 360 to 364 ft but a substantially lower percentage of survey-grid cells at elevations between 350 and 356 ft (fig. 47). The scour hole near pier 4 was slightly deeper along the right side in 2016 than in 2010, whereas the scour hole near pier 3 was slightly shallower in 2016 than in 2010 (fig. 49). The stone revetment on the banks showed no signs of substantial change except localized areas of deposition (fig. 49). As with all difference maps presented in this report, substantial deposition or scour apparent at the faces of the piers results from minor horizontal positional variances between the surveys (see the “Uncertainty Estimation” section).

The vertically averaged velocity vectors indicate mostly uniform flow throughout the reach, ranging from about 3 to 8 ft/s (fig. 50). Exceptions to uniform flow include minor to moderate turbulence in several transects, particularly near the mooring dolphins along the left (east) bank, near the moored barges, and downstream from the bridge piers (fig. 50).

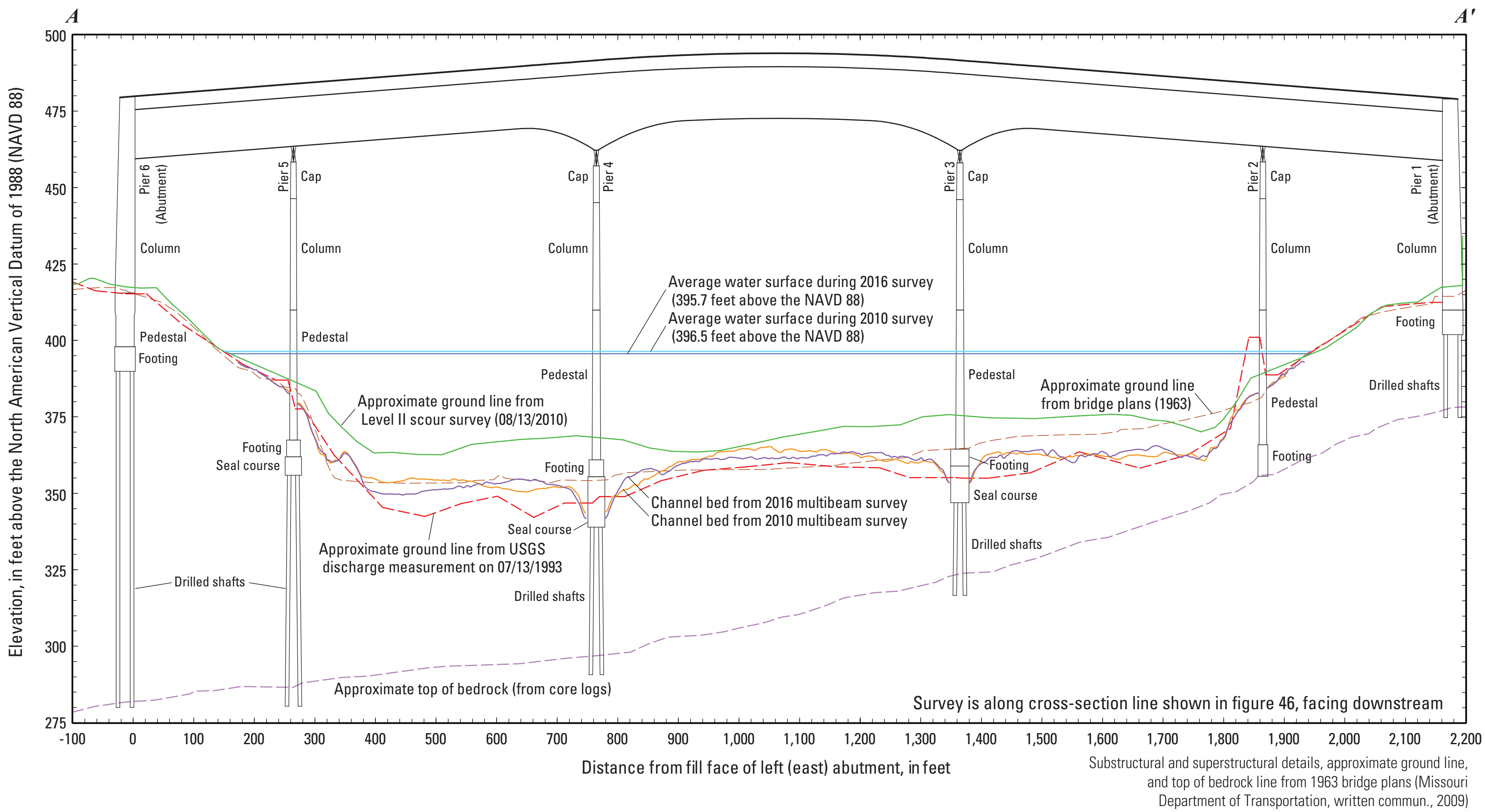


Figure 48. Profile showing kKey features, substructural and superstructural details, and surveyed channel bed of structure A1500 on Interstate 55 crossing the Mississippi River in St. Louis, Missouri.

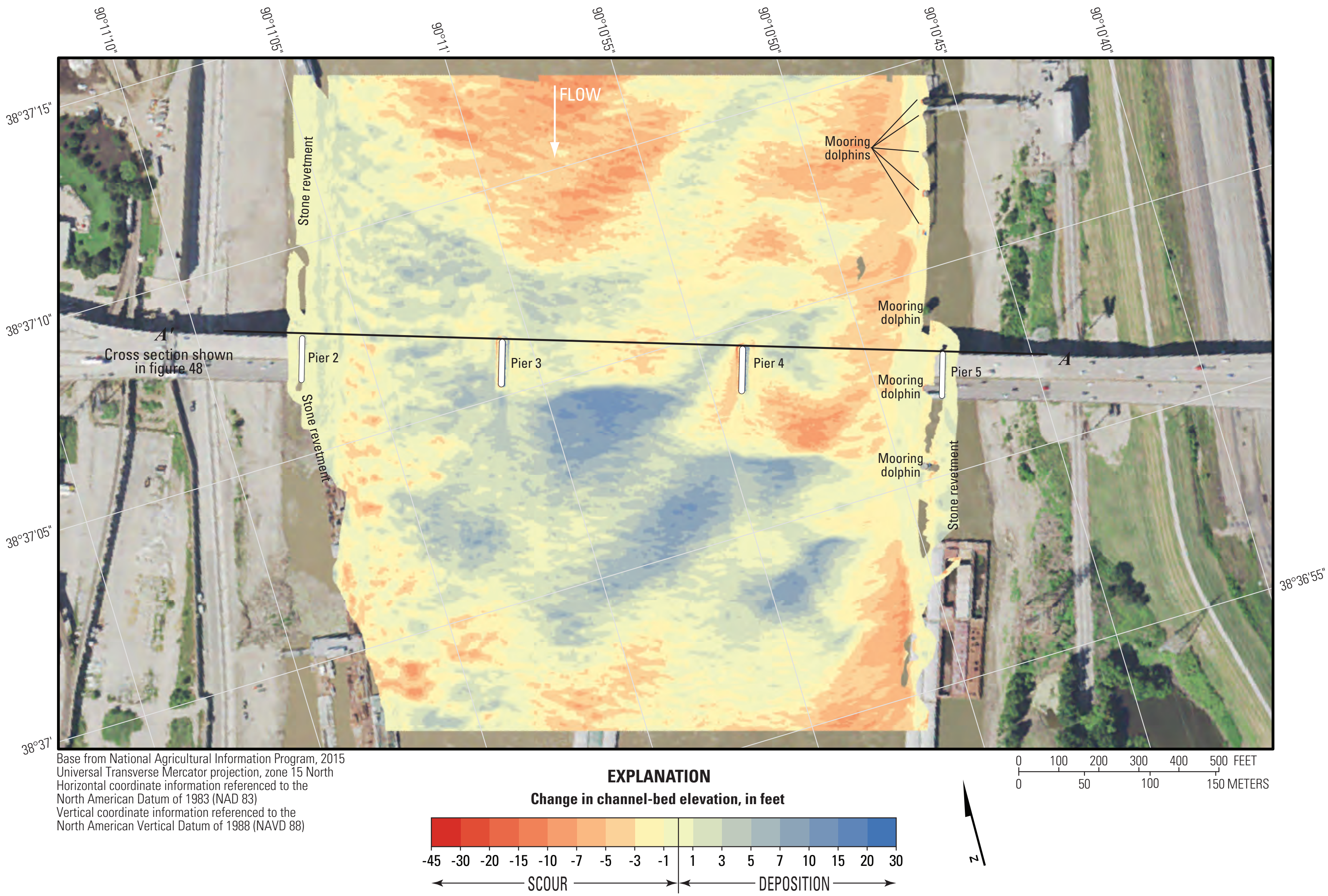


Figure 49. Difference between surfaces created from bathymetric surveys of the Mississippi River channel near structure A1500 on Interstate 55 in St. Louis, Missouri, on May 25, 2016, and October 20, 2010.

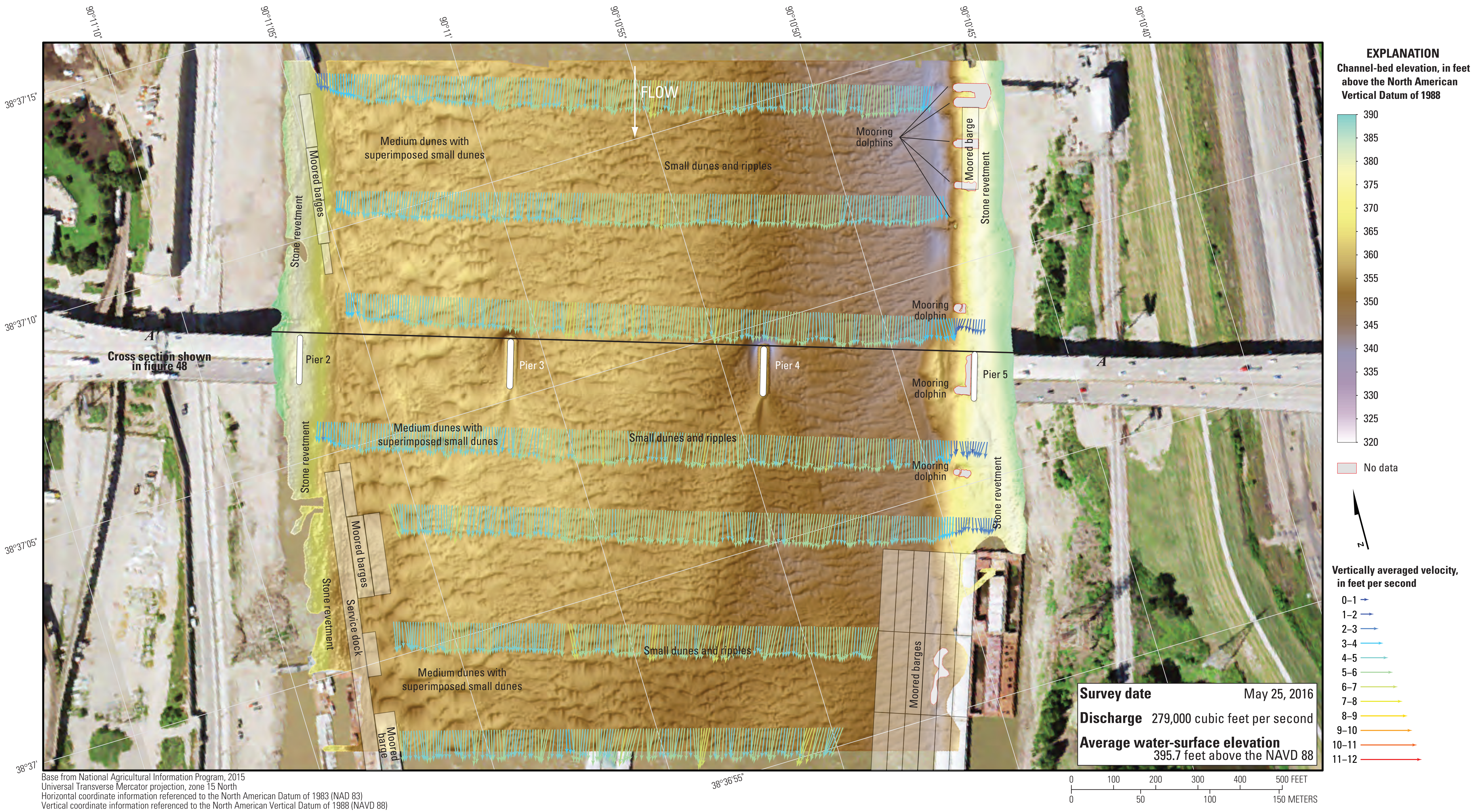


Figure 50. Bathymetry and vertically averaged velocities of the Mississippi River channel near structure A1500 on Interstate 55 in St. Louis, Missouri.

Structures A4936 and A1850 on Interstate 255

Structures A4936 and A1850 (site 35) are dual bridges on Interstate 255, crossing the Mississippi River at RM 168.8, on the southeastern side of the St. Louis metropolitan area between Mehlville, Mo., and Columbia, Illinois (fig. 1). The site was surveyed on May 26, 2016, and the average water-surface elevation near the bridge, determined by the RTK GNSS tide solution, was 390.5 ft (table 5). Flow on the Mississippi River was about 290,000 ft^3/s during the survey (table 5).

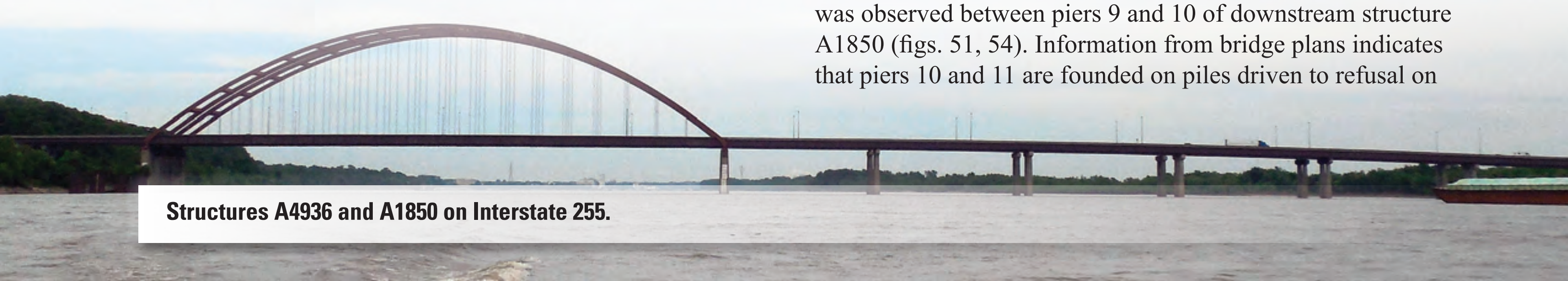
The survey area was about 1,640 ft long and varied in width from about 2,260 ft wide upstream from the L-head dike to about 1,640 ft wide at the downstream end (fig. 51). The survey area extended from bank to bank in the reach upstream from the L-head dike, and from the L-head dike to the right bank in the downstream part of the reach (fig. 51). The upstream end of the survey area was about 720 ft upstream from the centerline of structures A4936 and A1850 at pier 12 (fig. 51). The approximate channel-bed elevations ranged from about 350 to 375 ft for most of the surveyed area (5th to 95th percentile range of the bathymetric data; table 5; fig. 52), except near the L-head dike (fig. 51). A shallow thalweg was present along the right (west) bank throughout the reach and was about 3 to 7 ft deeper than the channel bed in the middle of the channel (fig. 51). The channel and thalweg deepened downstream from the bridges (fig. 51), likely because of the contraction of the channel caused by the L-head dike on the left bank. On the upstream left (northeast) side, deposits reached an elevation of about 377 ft (fig. 51). A line of medium dune features were detected along the toe of the right (west) bank, and numerous smaller dunes and ripples were present throughout the survey reach (fig. 51). A localized deep scour hole at the side of the L-head dike on the left bank had an approximate minimum channel-bed elevation of about 322 ft (fig. 51; table 5). As in previous surveys (Huizinga, 2011; Rydlund, 2009), a rock outcrop was present on the right (west) bank throughout the reach (fig. 51).

Substantial scour holes were present near piers 7, 8, and 9 of upstream structure A4936; and moderate scour holes were present near piers 7, 8, and 9 of downstream structure A1850 (fig. 51). Near pier 7 of upstream structure A4936, the scour hole had a minimum elevation of about 373 ft, about 12 ft below the average channel bed immediately upstream from the pier and 12 ft above the bottom of the seal course elevation of 361.00 ft (figs. 51, 53; table 8). The scour hole extended downstream around pier 7 of downstream structure A1850 (fig. 51) and had an approximate minimum channel-bed elevation of 374 ft near that pier (fig. 54; table 8). The scour holes did not extend below the bottom of the pedestals at either pier (figs. 53, 54). Information from bridge plans indicates that pier 7 of structures A4936 and A1850 are founded on piles driven to refusal on bedrock at both structures, and about 79 to 80 ft of bed material was present between the bottom of the scour holes and bedrock (figs. 53, 54; table 8).

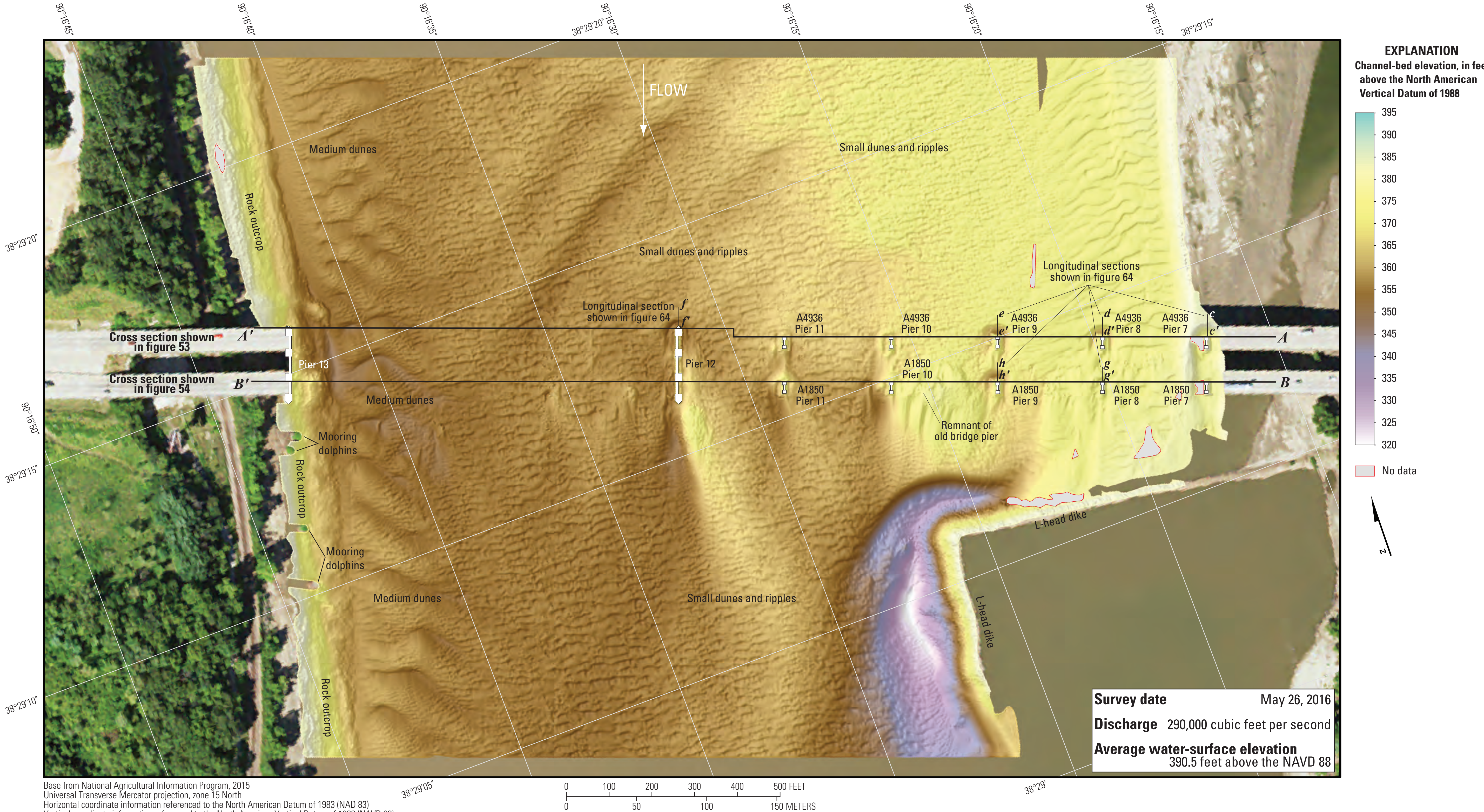
Near pier 8 of upstream structure A4936, the scour hole had an approximate minimum channel-bed elevation of about 360 ft, about 11 ft below the average channel bed immediately upstream from the pier and 7 ft above the bottom of the seal course elevation of 353.00 ft (figs. 51, 53; table 8). The scour hole exposed the footing and the top of the seal course at the upstream pier (fig. 53), and about 7 ft of channel-bed material was present above the bottom of the seal course elevation (table 8). At downstream structure A1850, the scour hole near pier 8 had an approximate minimum channel-bed elevation of 368 ft, about 6 ft below the average channel bed immediately upstream (fig. 51); however, the scour hole at the upstream pier extended downstream, partly affecting the scour near the downstream pier (table 8). Nonetheless, the scour hole at the downstream pier did not seem to extend below the pedestal (fig. 54), and about 15 ft of channel-bed material was present above the bottom of the seal course elevation (table 8). Information from bridge plans indicates that pier 8 of structures A4936 and A1850 are founded on piles driven to refusal on bedrock at both structures, and about 63 to 71 ft of bed material was present between the bottom of the scour holes and bedrock (figs. 53, 54; table 8).

Near pier 9 of upstream structure A4936, the scour hole had an approximate minimum channel-bed elevation of about 357 ft, about 10 ft below the average channel bed immediately upstream from the pier, and about 4 ft above the bottom of the seal course elevation of 353.00 ft (figs. 51, 53; table 8). At downstream structure A1850, the scour hole near pier 9 had a minimum channel-bed elevation of 357 ft, also about 10 ft below the average channel bed immediately upstream, and about 4 ft above the bottom of the seal course elevation of 353.00 ft (figs. 51, 54; table 8). Information from bridge plans indicates that pier 9 of structures A4936 and A1850 are founded on piles driven to refusal on bedrock at both structures, and about 60 ft of bed material was present between the bottom of the scour holes and bedrock (figs. 53, 54; table 8).

Scour holes were not observed upstream from piers 10 and 11 of either structure A4936 or A1850 (fig. 51); in fact, the surveyed channel bed seems to be aggraded near these piers (figs. 53, 54), which indicates riprap or some other scour-resistant material has been piled near the upstream faces of these piers; however, the side edges and downstream corners of the footings are apparent at pier 11 of both structures (appendix 1, figs. 1–9*C*, 1–9*D*), and a local scour hole with an approximate minimum channel-bed elevation of 352 ft was present near the downstream left corner of pier 11 of downstream structure A1850 (fig. 51; table 8). The remnant of an old bridge pier was observed between piers 9 and 10 of downstream structure A1850 (figs. 51, 54). Information from bridge plans indicates that piers 10 and 11 are founded on piles driven to refusal on



Structures A4936 and A1850 on Interstate 255.



Base from National Agricultural Information Program, 2015
Universal Transverse Mercator projection, zone 15 North
Horizontal coordinate information referenced to the North American Datum of 1983 (NAD 83)
Vertical coordinate information referenced to the North American Vertical Datum of 1988 (NAVD 88)

Figure 51. Bathymetric survey of the Mississippi River channel near structures A4936 and A1850 on Interstate 255 near St. Louis, Missouri.

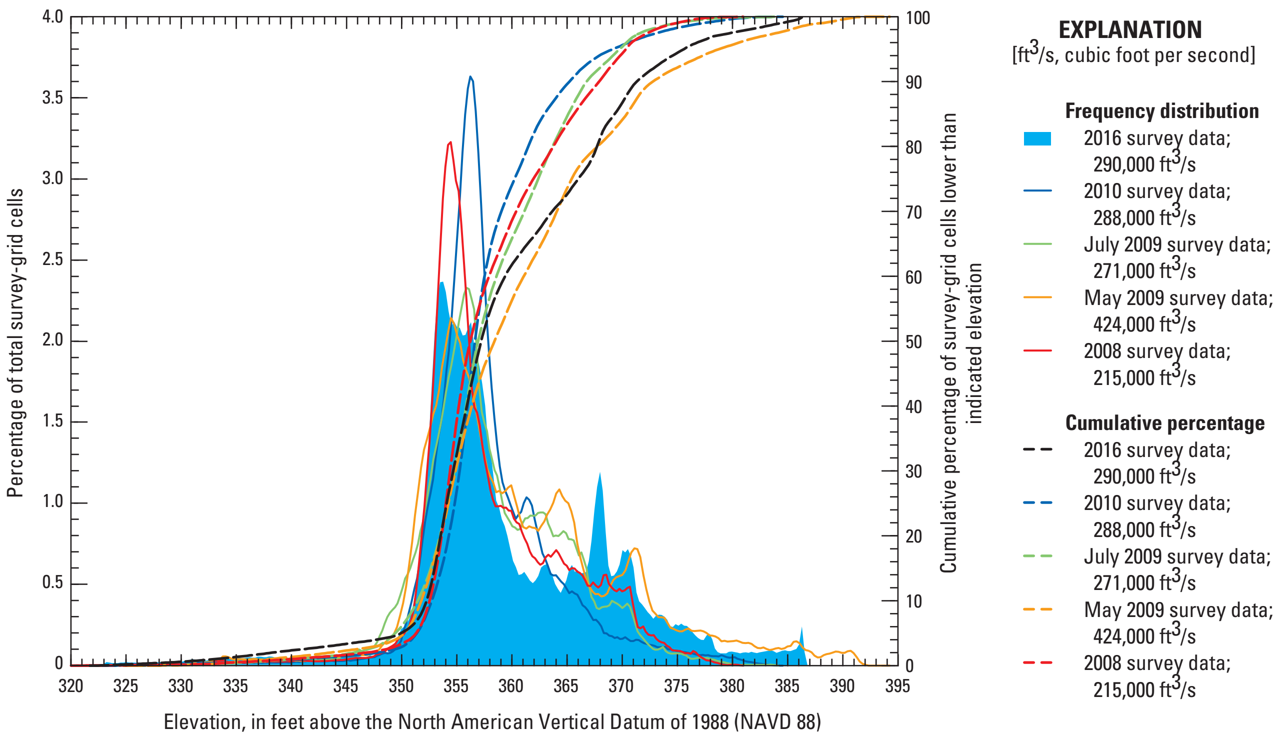


Figure 52. Frequency distribution of bed elevations for bathymetric survey-grid cells on the Mississippi River near structures A4936 and A1850 on Interstate 255 near St. Louis, Missouri, on May 26, 2016, compared to previous surveys.

bedrock at both structures, and about 59 to 66 ft of bed material was present between the approximate minimum channel-bed elevation near each pier and bedrock (figs. 53, 54; table 8).

A minor to moderate scour hole was present upstream from pier 12 with a minimum elevation of about 349 ft, about 6 ft below the average channel bed immediately upstream from the pier, but 21 ft above the bottom of the seal course elevation of 328.00 ft (figs. 51, 53, 54; table 8). Information from bridge plans indicates that pier 12 is founded on piles driven to refusal on bedrock, and about 56 ft of bed material was present between the bottom of the scour hole and bedrock (figs. 53, 54; table 8).

The vertically averaged velocity vectors indicate mostly uniform flow throughout the channel, ranging from about 2 to 9 ft/s (fig. 55). Flow was angled to the right (west) in the transects immediately upstream and adjacent to the L-head dike because of the constricting effect of the dike (fig. 55). Exceptions to uniform conditions include moderate turbulence observed in all the transects, and substantial velocity gradients and flow reversal in the area adjacent to the L-head dike (fig. 55). The piers generally seem to be aligned with flow (fig. 55).

Given the generally low velocities observed along the left (east) bank in the upstream part of the reach, which obviously results in deposition in the area along the upstream left bank, the size of the scour holes around piers 7 through 9—and particularly near pier 7—perhaps are unexpected; however, velocities upstream from piers 8 and 9 were around 5 to 6 ft/s in the current (2016) survey (fig. 55), which are of sufficiently high magnitude to create a moderate to substantial scour hole in a sand-bed channel like the Mississippi River, dependent upon the cross-sectional size and shape of the pier (Richardson and Davis, 2001). Furthermore, during the survey on May 12–13, 2009, completed as part of the fixed scour-monitor study at this site (Rydlund, 2009; full bathymetry shown in Huizinga and others [2010] and included with the data from this report), flow conditions were such that flow was over the L-head dike (Huizinga and others, 2010, fig. 11). Although velocity data were not collected during that survey, the researchers recollect experiencing substantial velocities around piers 7 through 9 of a magnitude similar to those observed further to the right in the channel when there was flow over the L-head dike.

As indicated in the previous paragraph, real-time scour monitoring of the scour hole at pier 12 happened at this site in 2008–2009 using fixed, single-beam acoustic transducers attached to the upstream and downstream nose of pier 12 (Rydlund, 2009). Three bathymetric surveys of the area were completed at a variety of flow conditions as part of that study for verification of data received from the fixed transducers; furthermore, this site was part of the previous study of sites on the Missouri and Mississippi Rivers near St. Louis (Huizinga, 2011). As in the preceding discussions at each site in the St. Louis area, the differences between the current (2016) survey at this site and the previous surveys will be examined and discussed in reverse chronological order.

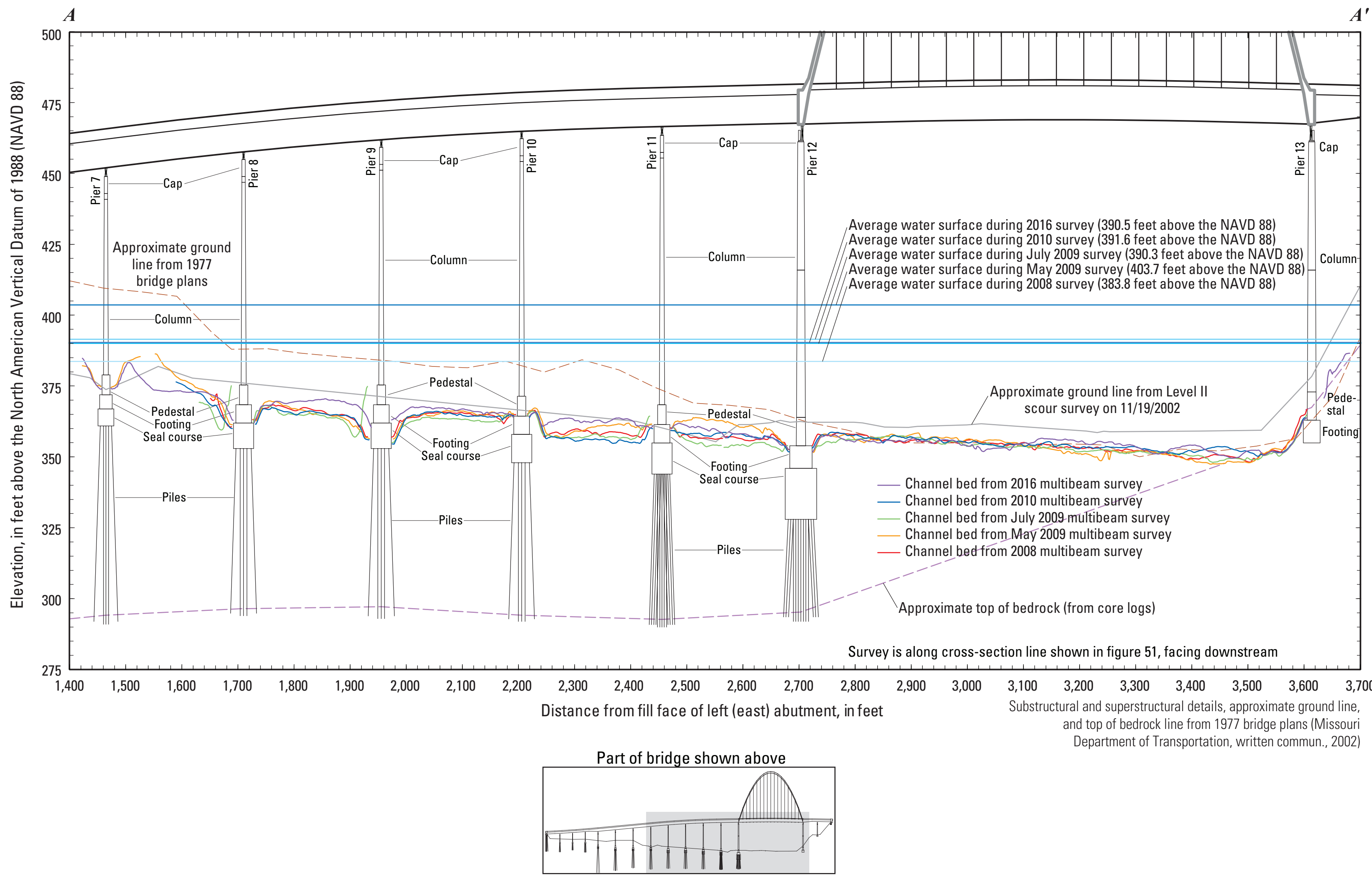


Figure 53. Key features, substructural and superstructural details, and surveyed channel bed of structure A4936 on Interstate 255 crossing the Mississippi River near St. Louis, Missouri.

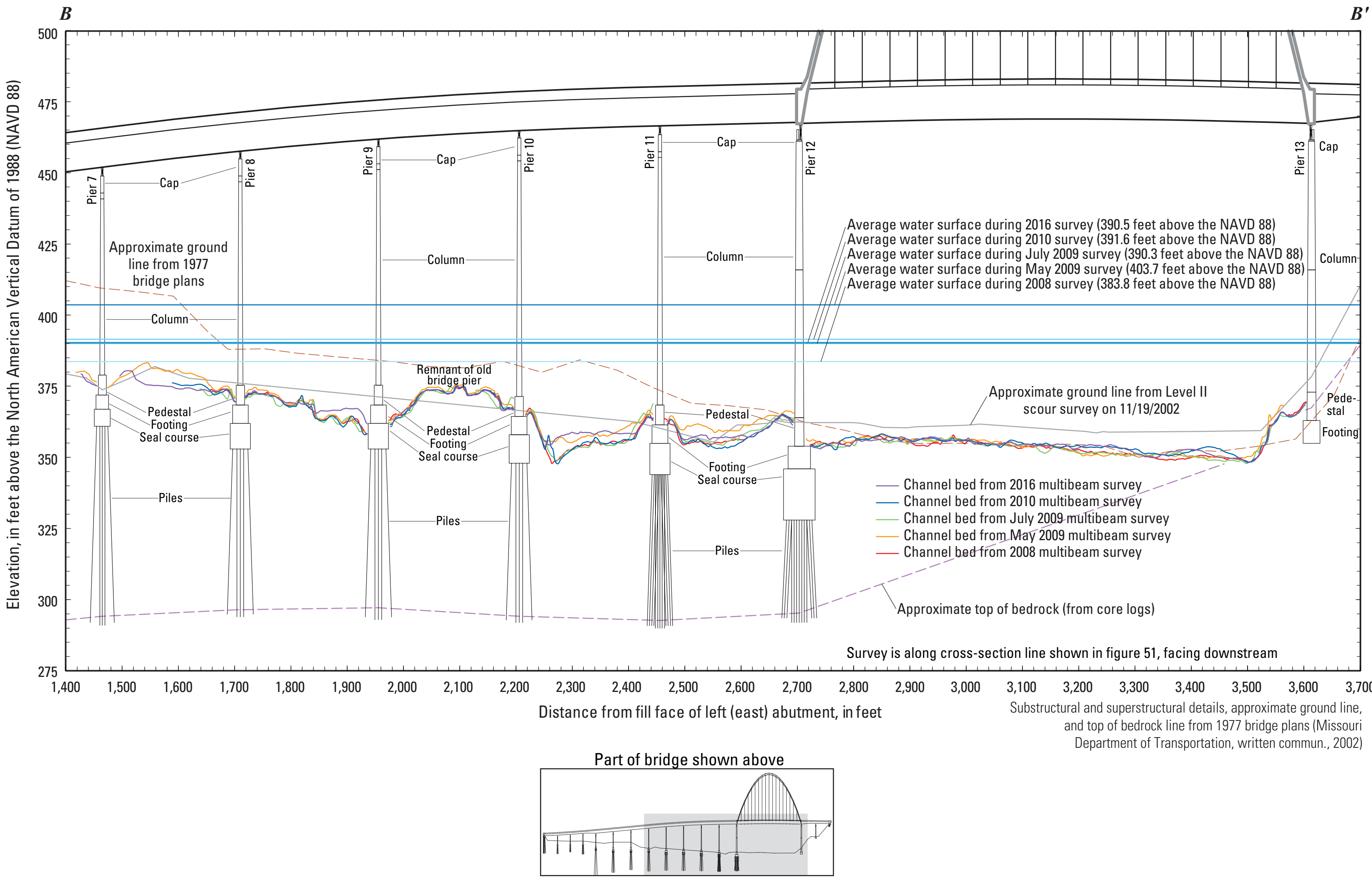


Figure 54. Key features, substructural and superstructural details, and surveyed channel bed of structure A1850 on Interstate 255 crossing the Mississippi River near St. Louis, Missouri.

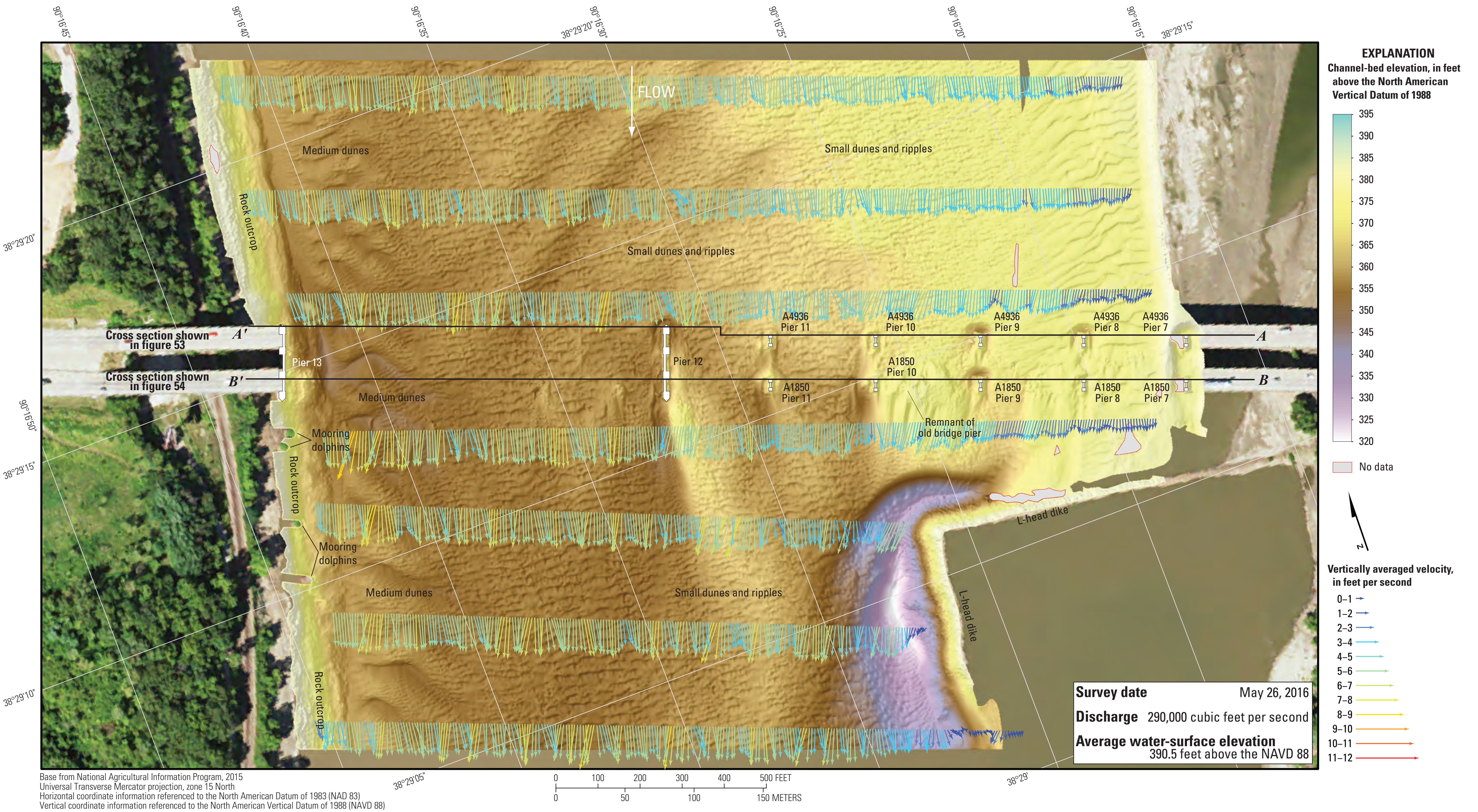


Figure 55. Bathymetry and vertically averaged velocities of the Mississippi River channel near structures A4936 and A1850 on Interstate 255 near St. Louis, Missouri.

The difference between the survey on May 26, 2016, and the previous survey on October 19, 2010 (fig. 56), indicates an approximate balance of scour and deposition (a mean difference of +0.77 ft between the bathymetric surfaces) throughout the reach from 2010 to 2016 (table 7). The net volume of cut in the reach from 2010 to 2016 was about 53,800 yd^3, and the net volume of fill was about 140,500 yd^3, resulting in a net gain of about 86,700 yd^3 of sediment between 2010 and 2016. There was moderate to substantial deposition of more than 10 ft in the scour holes upstream from piers 8 and 9 of upstream structure A4936 between 2010 and 2016 (fig. 56). There was a general area of moderate deposition in the left (east) side of the channel throughout the reach, an area of moderate scour on the far left (east) side along the bank, and a balance of minor to moderate scour and deposition in the rest of the channel between piers 12 and 13 on the right (west) bank (fig. 56). The cross sections from the 2016 survey compared to the 2010 survey show the pattern of deposition, particularly between piers 8 and 11, whereas the section lines are similar to one another between pier 12 and pier 13 on the right bank in all the surveys (figs. 53, 54). The frequency distribution of bed elevations was of a similar shape in 2016 compared to 2010; however, a lower percentage of survey-grid cells were at elevations between 352 and 357 ft, and a higher percentage of survey-grid cells were at elevations between 365 and 375 ft than in 2010 (fig. 52). The rock outcrops on the right (west) bank seem to have experienced localized deposition, whereas the structure of the L-head dike appears to have experienced minor scour (fig. 56), but this may be partly a function of positional variations between the surveys. As with all difference maps presented in this report, substantial deposition or scour apparent at the faces of the piers likely results from minor horizontal positional variances between the surveys (see the “Uncertainty Estimation” section).

The difference between the survey on May 26, 2016, and the survey on July 8, 2009 (fig. 57), also indicates an approximate balance of scour and deposition (a mean difference of +0.51 ft between the bathymetric surfaces) throughout the reach from July 2009 to 2016 (table 7). The net volume of cut in the reach from July 2009 to 2016 was about 97,400 yd^3, and the net volume of fill was about 152,200 yd^3, resulting in a net gain of about 54,800 yd^3 of sediment between July 2009 and 2016. There was moderate to substantial deposition of more than 10 ft in the scour holes upstream from piers 8 and 9 of upstream structure A4936, and moderate scour near pier 10, as well as downstream from pier 12 of both structures A4936 and A1850 between July 2009 and 2016 (fig. 57). There was a general area of moderate deposition in the left (east) side of the channel at and upstream from the bridges, an area of moderate scour in the middle of the channel near the upstream and downstream ends of the reach, and a balance of minor to moderate scour and deposition along the right (west) bank (fig. 57). The cross sections from the 2016 survey compared to the July 2009 survey show the pattern of deposition, particularly between piers 10 and 12, whereas the section lines are similar to one another between pier 12 and pier 13 on the right bank in all the surveys (figs. 53, 54). The frequency distribution of bed elevations was of a similar shape in 2016 compared to July 2009, albeit with a lower percentage of survey-grid cells at elevations between 358 and 366 ft and a higher percentage of survey-grid cells at elevations between 366 and 380 ft than in July 2009 (fig. 52). The rock outcrops on the right (west) bank seem to have experienced localized deposition, as did the structure of the L-head dike (fig. 57), but it is uncertain how much of this apparent difference is a function of positional variations between the surveys. Position information for surveys before 2010 were not processed through POS-Pac™ MMS™, and therefore have more questionable positional accuracy, particularly near the bridges where GNSS signal might be lost. As with all difference maps presented in this report, substantial deposition or scour apparent at the faces of the piers likely results from minor horizontal positional variances between the surveys (see the “Uncertainty Estimation” section).

The difference between the survey on May 26, 2016, and the survey on May 12–13, 2009 (fig. 58), also indicates an approximate balance of scour and deposition (a mean difference of –0.17 ft between the bathymetric surfaces) throughout the reach from May 2009 to 2016 (table 7). The discharge during the May 2009 survey was 424,000 ft^3/s (table 7), which is close to the 50-percent annual exceedance probability (2-year recurrence interval) flood discharge of 450,000 ft^3/s for the streamgage at St. Louis (U.S. Army Corps of Engineers, 2004a, table D–28). However, the net volume of cut in the reach from May 2009 to 2016 was about 131,800 yd^3, and the net volume of fill was about 111,500 yd^3, resulting in a net loss of only about 20,300 yd^3 of sediment between May 2009 and 2016. There was moderate deposition of over 6 ft in the scour holes upstream from piers 8 and 9 of upstream structure A4936, and moderate scour near pier 10 as well as downstream from pier 12 of both structures A4936 and A1850 between May 2009 and 2016 (fig. 58). There was a general area of minor to moderate deposition in the left (east) side of the channel upstream from the bridges and in the middle of the channel downstream from the bridges, with an area of moderate scour in the middle to right side of the channel upstream from the bridge and between piers 11 and 12, and a balance of minor to moderate scour and deposition along the right (west) bank as in the other surveys (fig. 58). There was substantial scour of over 15 ft along the left (west) bank, and in the scour hole created by flow around the L-head dike (fig. 58). The cross sections from the 2016 survey compared to the May 2009 survey show the similarities of the sections, except between piers 7 and 8 and between piers 11 and 12 (figs. 53, 54). The frequency distribution of bed elevations was of a remarkably similar shape in 2016 compared to May 2009, albeit with a lower percentage of survey-grid cells at elevations between 358 and 366 ft and a higher percentage of survey-grid cells at elevations between 366 and 369 ft than in May 2009 (fig. 52). The frequency distribution and cumulative percentage curve of the 2016 survey are most similar to the May 2009 curves, despite the difference of discharge of

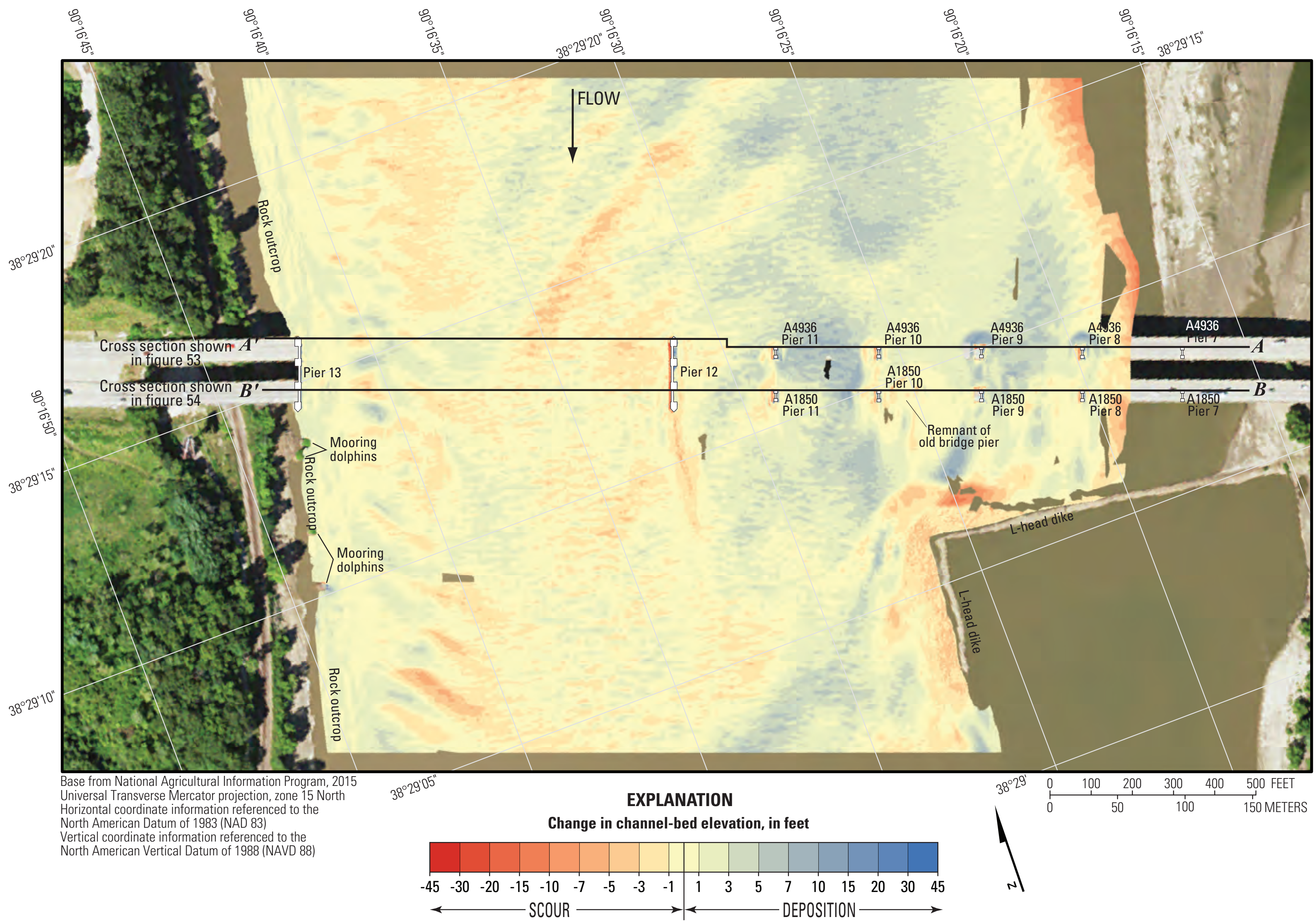


Figure 56. Difference between surfaces created from bathymetric surveys of the Mississippi River channel near structures A4936 and A1850 on Interstate 255 near St. Louis, Missouri, on May 26, 2016, and October 19, 2010.

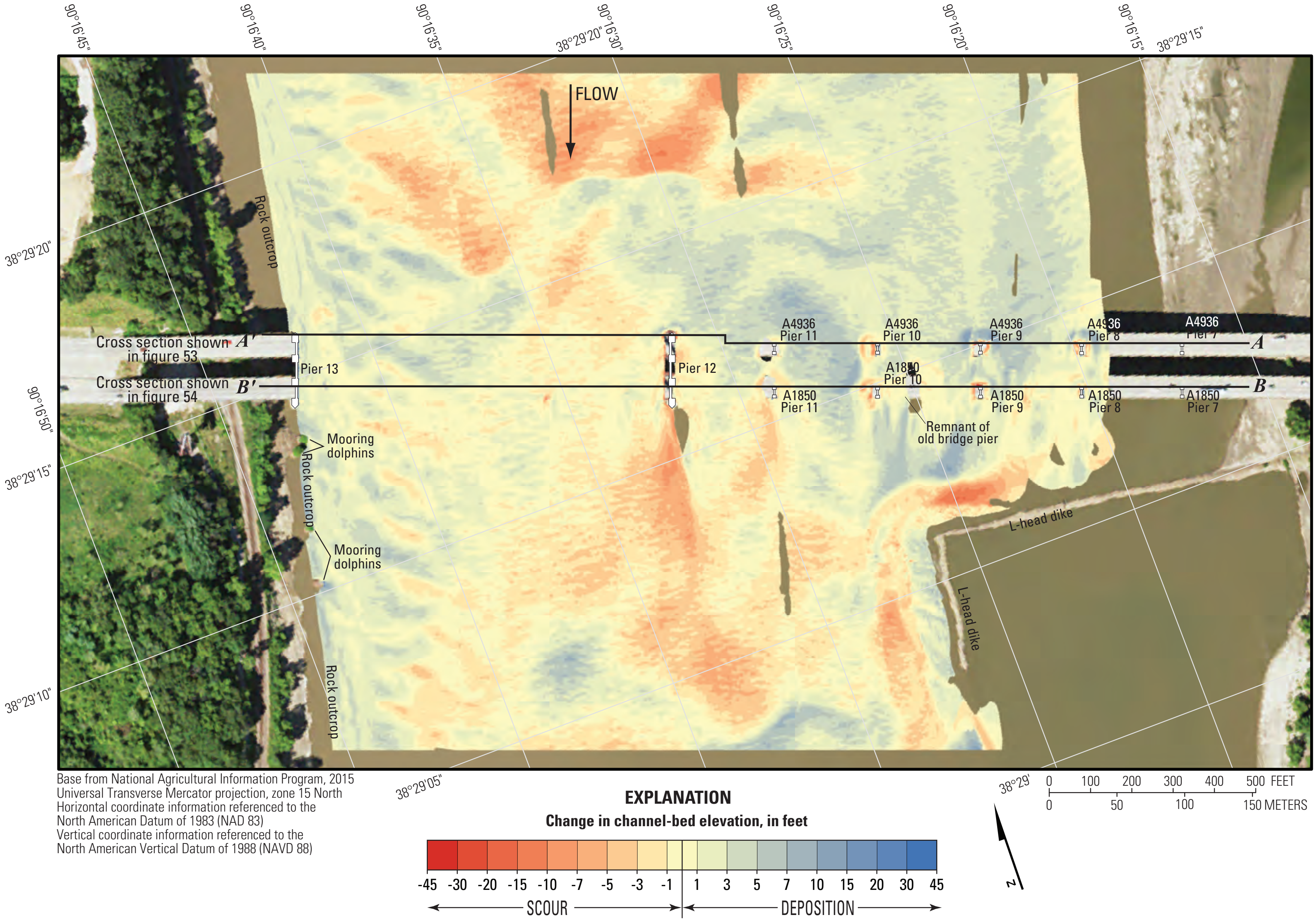


Figure 57. Difference between surfaces created from bathymetric surveys of the Mississippi River channel near structures A4936 and A1850 on Interstate 255 near St. Louis, Missouri, on May 26, 2016, and July 8, 2009.

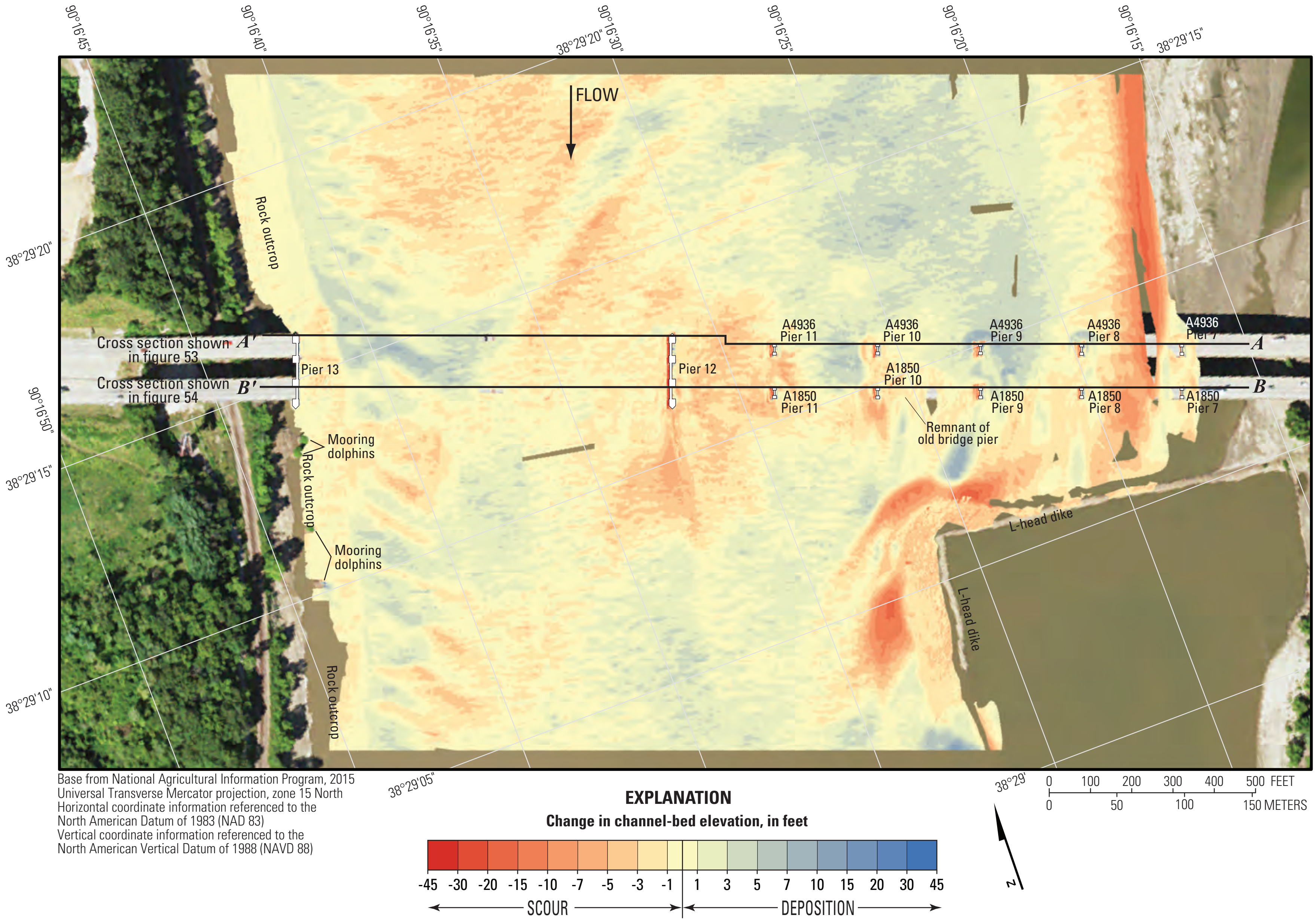


Figure 58. Difference between surfaces created from bathymetric surveys of the Mississippi River channel near structures A4936 and A1850 on Interstate 255 near St. Louis, Missouri, on May 26, 2016, and May 12–13, 2009.

134,000 ft^3/s between May 2009 and 2016 (fig. 52; table 7). The rock outcrops on the right (west) bank appear to have experienced localized scour, as did the structure of the L-head dike (fig. 58), but it is presumed much of this apparent difference is a function of positional variations between the surveys. As mentioned in the previous paragraph, position information for surveys before 2010 were not processed through POS-Pac™ MMS™, and therefore have more questionable positional accuracy, particularly near the bridges where GNSS signal might be lost. As with all difference maps presented in this report, substantial deposition or scour apparent at the faces of the piers likely results from minor horizontal positional variances between the surveys (see the "Uncertainty Estimation" section), particularly with data near the bridge before 2010.

The difference between the survey on May 26, 2016, and the survey on October 2–3, 2008 (fig. 59), also indicates an approximate balance of scour and deposition (a mean difference of +0.53 ft between the bathymetric surfaces) throughout the reach from 2008 to 2016 (table 7). The net volume of cut in the reach from 2008 to 2016 was about 70,300 yd^3, and the net volume of fill was about 126,400 yd^3, resulting in a net gain of about 56,100 yd^3 of sediment between 2008 and 2016. There was moderate deposition of over 8 ft in the scour hole upstream from pier 8 of upstream structure A4936, moderate to substantial deposition of over 10 ft in the scour hole upstream from pier 9 of upstream structure A4936, and moderate scour downstream from piers 10 and 12 of both structures A4936 and A1850 between 2008 and 2016 (fig. 59). There was a general area of minor to moderate scour in the middle of the channel throughout the reach, whereas there was minor to moderate deposition on both sides of the channel (fig. 59). There was substantial scour of more than 20 ft in the scour hole created by flow around the L-head dike (fig. 59). The cross sections from the 2008 survey were similar to the July 2009 and 2010 surveys, so the comparison to the 2016 sections show the pattern of deposition, particularly between piers 10 and 12, whereas the section lines are similar to one another between pier 12 and pier 13 on the right bank in all the surveys (figs. 53, 54). As in all the surveys at this site, the frequency distribution of bed elevations was of a similar shape in 2016 compared to 2008, albeit with a lower percentage of survey-grid cells at elevations between 352 and 356 ft and between 358 and 365 ft, and a higher percentage of survey-grid cells at elevations between 365 and 385 ft than in 2008 (fig. 52). The rock outcrops on the right (west) bank appear to have experienced localized deposition, whereas the structure of the L-head dike appears to have experienced localized moderate scour (fig. 59), but it is presumed much of this apparent difference is a function of positional variations between the surveys. As mentioned in the previous paragraph, position information for surveys before 2010 were not processed through POS-Pac™ MMS™, and therefore have more questionable positional accuracy, particularly near the bridges where GNSS signal might be lost. As with all difference maps presented in this report, substantial deposition or scour apparent at the faces of the piers likely results from minor horizontal positional variances between the surveys (see the "Uncertainty Estimation" section), particularly with data near the bridge before 2010.

General Findings and Implications

Several of the findings at each surveyed bridge were common to all the bridges, and some findings were evident only when results of the surveys were examined as a set. These general findings are of benefit in the assessment of scour at the surveyed bridges, as well as other bridges close by or in similar settings.

Effects of Low to Moderate Flooding Compared to Previous Surveys

Richardson and Davis (2001) separate long-term aggradation and degradation of a channel from the contraction and local scour that happens at a bridge site during floods. Contraction scour is the general change in the channel-bed elevation across a bridge opening resulting from the passage of a flood through a constriction, where more material is in suspension and transport. Local scour is the localized erosion of material caused by flow vortex action that forms near bridge piers and abutments. Although all the scour processes (long term, contraction, and local scour) continually are at work, contraction and local scour generally are cyclic for the live-bed scour typically observed in alluvial channels and generally result in a decrease and subsequent increase of the channel-bed elevation during a flood.

Because of the myriad number and interactions of factors affecting sediment transport conditions and the resultant bed configuration, it is recognized as simplistic to assume that the configuration and size of bed forms observed during the current (2016) surveys near St. Louis (fig. 1) are dependent only upon the instantaneous discharge at a given site. While it is beyond the scope of the current (2016) study to examine all of the antecedent conditions that created the observed channel-bed configuration, the following discussion attempts to draw conclusions based on the conditions observed at each site during the current (2016) and previous surveys.

A comparison of the dune sizes at the various sites is indicative of the different flow regimes between 2011 and 2016 at the Missouri River sites (sites 23 to 27). Whereas many of the surveys in 2011 had medium to large dune features, the 2016 surveys were filled throughout with mostly small to medium dune features and ripples (figs. 6, 13, 20, 27, and 34). The largest dune features in the 2016 surveys were observed at dual bridge structure A5585 (site 24, fig. 13). The smaller size and amplitude of the dune features compared to 2011 indicates less bed-material and bedload transport because of the lower flow values (Simons and others, 1965).

Many flood durations on the Missouri and Mississippi Rivers near St. Louis can be measured in days to weeks because of the large upstream contributing drainage area;

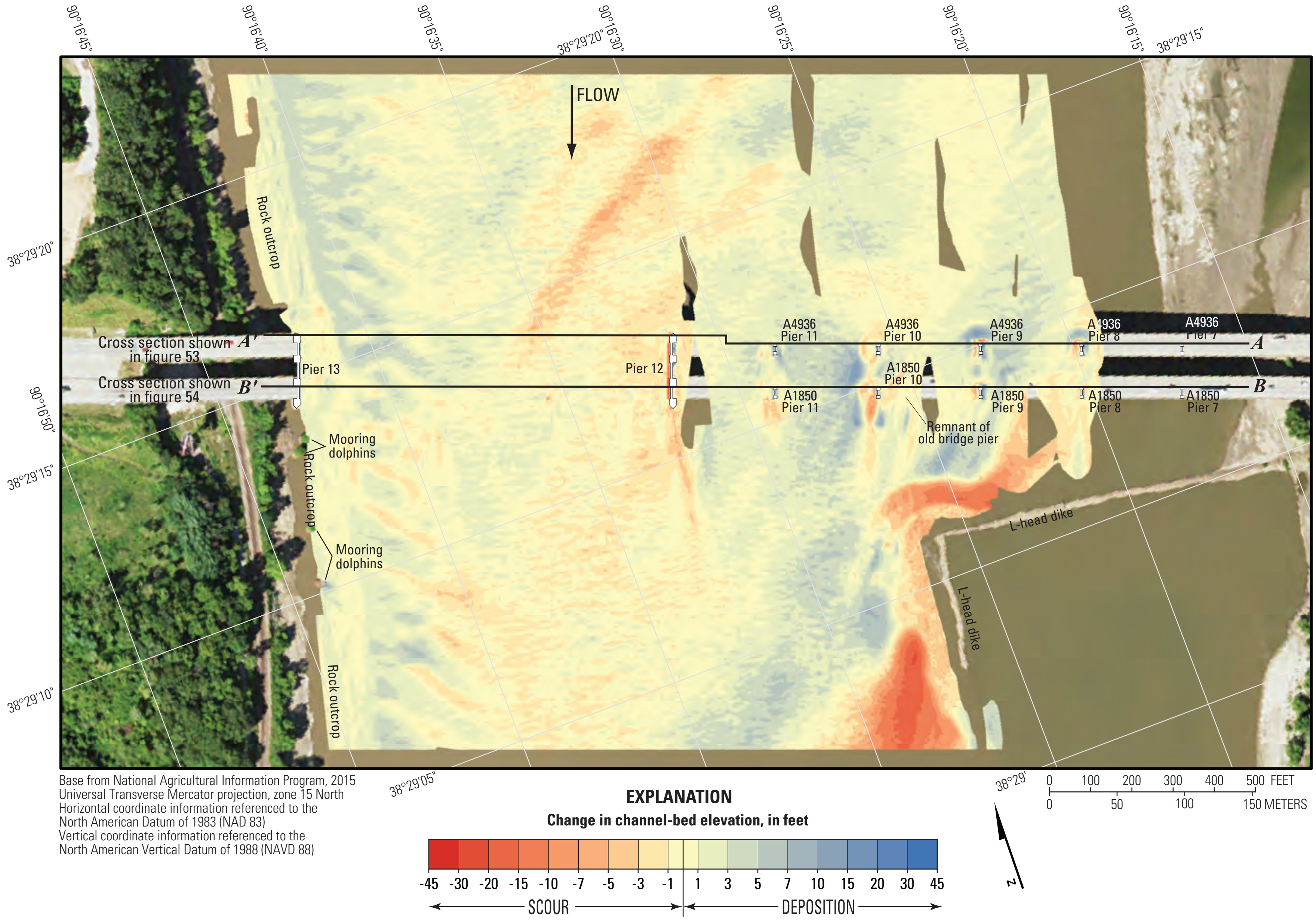


Figure 59. Difference between surfaces created from bathymetric surveys of the Mississippi River channel near structures A4936 and A1850 on Interstate 255 near St. Louis, Missouri, on May 26, 2016, and October 2–3, 2008.

however, as described in the "Description of Flow Conditions" section earlier in this report, most of the surveys in this study happened during a trough between flood rises during generally higher late-spring flows (fig. 2). The fixed scour monitors on structures L0550 and A4497 at Jefferson City, Mo., about 145 river miles upstream from the St. Louis metropolitan area, discussed in Huizinga (2014) indicate that many of the local scour holes observed at the upstream nose of the piers at that site did not fill in rapidly after the recession of a flood (Huizinga, 2014, fig. 35); nevertheless, flood recession generally leads to deposition rather than scour. Examining results based purely on instantaneous discharge and ignoring effects from antecedent flow conditions, it might be reasonable to assume that the scour holes near the piers and the general scour observed under the bridge crossings might be of an equal to lesser magnitude than that observed during the previous surveys during the July/August 2011 flood, and of an equal to greater magnitude during the previous surveys during generally lower flow in 2010. Generally, this assumption proved to be true, with only minor exceptions.

Flow rates at the Missouri River sites (sites 23 to 27) during the 2016 surveys ranged from about 20 to 50 percent greater than the 2010 flow rate, and water-surface elevations were 1.5 to 3.5 ft higher in 2016 than in 2010 (table 7). The average difference (statistical mean) between the bathymetric surfaces varied from 1.8 ft lower to 0.9 ft higher in 2016 than 2010 (table 7). Alternatively, flow rate at the Missouri River sites during the 2016 surveys ranged from about 49 to 58 percent of the 2011 flow rate, and water-surface elevations were about 7 to 9 ft lower in 2016 than in 2011 (table 7), and the average difference (statistical mean) between the bathymetric surfaces varied from 0.3 ft lower to 2.2 ft higher in 2016 than 2011 (table 7). When the average channel-bed elevation is examined with time (fig. 60), there generally appears to be only small variation in the average channel-bed elevations at a given site on the Missouri River, and generally, the average channel-bed elevation of the 2016 surveys fell between the two previous surveys, as might be expected given the discharge ratios of the 2016 compared to the previous surveys. However, average channel-bed elevation at structures A3292/L0561 (site 25) was higher in 2016 than in either 2010 or 2011, and the average channel-bed elevation at dual bridge structure A5585 (site 24) is closer to the 2011 bed elevation than is seen at other sites on the Missouri (table 7; fig. 60). Structures A3292/L0561 in particular had a positive average difference between the bathymetric surfaces from 2016 to 2011 and from 2016 to 2010 (table 7), the only site to be so. This configuration of average channel-bed elevations and average differences shows that greater discharge alone does not necessarily result in more scour at a site (as would be evidenced by lower average channel-bed elevations with increased discharge).

The lack of variability in the average channel-bed elevations at dual bridge structure A4557 (site 26) and structure A3047 (site 27) further downstream may indicate these sites are at or near a local feature that controls sediment deposition and scour. At dual bridge structure A4557, the feature may be a combination of the constriction at structures A3292/L0561 (site 25) upstream (fig. 20) and being near the downstream end of the relatively straight reach of river between structures A3292/L0561 and dual bridge structure A4557 (fig. 1); sediment may be pulled into suspension in the constriction and unable to be deposited near dual bridge structure A4557 until the next river bend downstream (fig. 1). Deposition upstream from the constriction at structures A3292/L0561 also may explain the trend in the average channel-bed elevations seen at dual bridge structures A5585 (site 24; fig. 60). Unfortunately, there are no other bridges near structure A3047 (site 27) from which any conclusions about scour or deposition in the vicinity of A3047 can be drawn.

Flow rates at sites 34 and 35 on the Mississippi River during the 2016 surveys were less than 1 percent different than the 2010 flow rates, and about 6 percent lower than the 2009 flow rate at site 33 (table 7), implying similar, nonflood conditions during both surveys at each site. Water-surface elevations were about 1 to 2 ft lower in 2016 than in the previous nonflood survey (table 7), and the average difference (statistical mean) between the bathymetric surfaces varied from 1.4 ft lower to 0.8 ft higher in 2016 than the previous survey (table 7). When the average channel-bed elevation is examined with time (fig. 60), there is more variation in the average channel-bed elevations at a given site on the Mississippi River than on the Missouri River, and the average channel-bed elevation of the 2016 surveys fell above the previous survey, as might be expected given the discharge ratios of the 2016 compared to the previous survey.

In the multiple surveys at structures A4936/A1850 (site 35), the flow rate of the May 2009 survey was high enough to be considered a "flood" survey, with the 2016 flow rate being about 68 percent of the May 2009 flow rate and similar in magnitude to the 2011 flood as measured at the streamgage at St. Charles, Mo. The water-surface elevation was over 13 ft lower in 2016 than in May 2009 (table 7), but the average channel-bed elevation was only 0.2 ft lower in 2016 than in May 2009 (table 7). In fact, in all the surveys at this site, the average difference between the bathymetric surfaces only ranged from 0.2 ft lower to 0.8 ft higher, regardless of the flow conditions (table 7).

An examination of the frequency distributions of bed elevations in the 2016 surveys compared to the previous surveys reveals additional differences that may be the result of flow conditions during the 2016 surveys (fig. 61). The frequency distributions generally were narrower in the 2016 survey than in the 2011 survey at each site, with a higher percentage of survey-grid cells in a particular elevation range (fig. 61*A*). The narrower distribution curves result in generally steeper cumulative percentage curves in 2016 than in 2011, but not as steep as in 2010 (fig. 61*B*). Cumulative percentage curves that are steep indicate a channel bed with a narrower range of elevations (more level throughout the reach), whereas those that are less steep indicate a wider variation of elevations. Cumulative percentage curves with "steps" indicate a channel with distinct

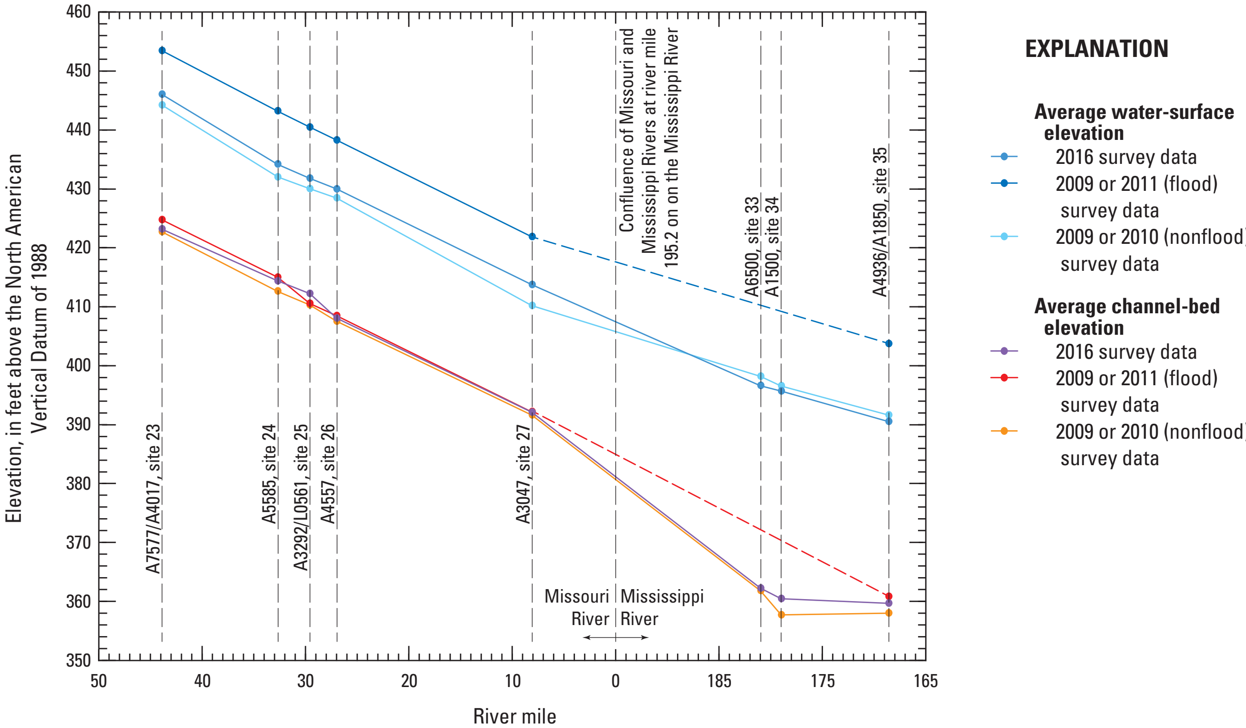


Figure 60. Average channel-bed and water-surface elevations near bridges on the Missouri and Mississippi Rivers near St. Louis, Missouri, from surveys in 2009, 2010, 2011, and 2016.

groups of elevations, such as thalweg on one side and a shallow area on the opposite side of the channel (such as structure A3047, figs. 34 and 35); however, some of the steps in the cumulative percentage curves are the result of collecting more information higher on the banks by tilting the MBES head in the later surveys than was done in 2010.

The frequency distributions seem to confirm the hypothetical scenario of a sediment control feature near dual bridge structure A4557 postulated in the average channel-bed elevation curve discussion above. The frequency distribution curves for structures A7577/A4017 and structures A3292/L0561 have local maxima with a higher percentage of survey-grid cells than other sites on the Missouri (fig. 61*A*). As would be expected, these maxima are at a lower elevation than sites upstream from them and generally at a higher elevation than most of sites downstream; however, the distribution curve for dual bridge structure A4557 consistently has a local maximum that is at a higher elevation than the next upstream site, and the cumulative percentage curve is close to and occasionally to the right of (implying a higher elevation than) the next upstream site in the surveys (fig. 61*B*).

The similarity of the frequency distributions and cumulative percentage curves of the Mississippi River sites (sites 33–35) is remarkable (fig. 61*B*). Whereas the Missouri River sites exhibit a relatively constant bed slope throughout the reach, the Mississippi River sites are substantially lower, and all have similar average channel-bed elevations (fig. 60; table 5), despite the distance between the upstream and downstream sites. The similarity of channel-bed elevations cause the cumulative percentage curves to be very similar to one another, as well as to plot close together (fig. 61*B*). Part of the difference in bed slope may be the result of the Chain of Rocks, the remains of a natural geologic formation and an old river control structure (Missouri Department of Conservation, 2017), which creates a grade control of the river downstream from structure A0890 on Interstate 270 and the Old Chain of Rocks Bridge (fig. 1), resulting in a difference in the channel-bed elevation upstream and downstream of this feature. Unfortunately, data have not been collected at either structure A6500 or A1500 during a flood comparable to the May 2009 event surveyed at structures A4936/A1850 or the 2011 event on the Missouri River.

Size and Shape of Scour Holes

Scour holes were observed at most piers in the main channel area, except those on banks or surrounded by riprap or debris rafts. As discussed in summaries of previous bathymetric surveys in Missouri (Huizinga, 2010, 2011, 2012, 2014, 2015, 2016), the size and shape of these holes often was different from pier to pier because pier scour is a function of several factors, including the depth and velocity of approach flow, the width and nose shape of the pier, and the angle of approach flow (Richardson and Davis, 2001). The effect of several of these factors on scour holes observed during the 2016 surveys are discussed below.

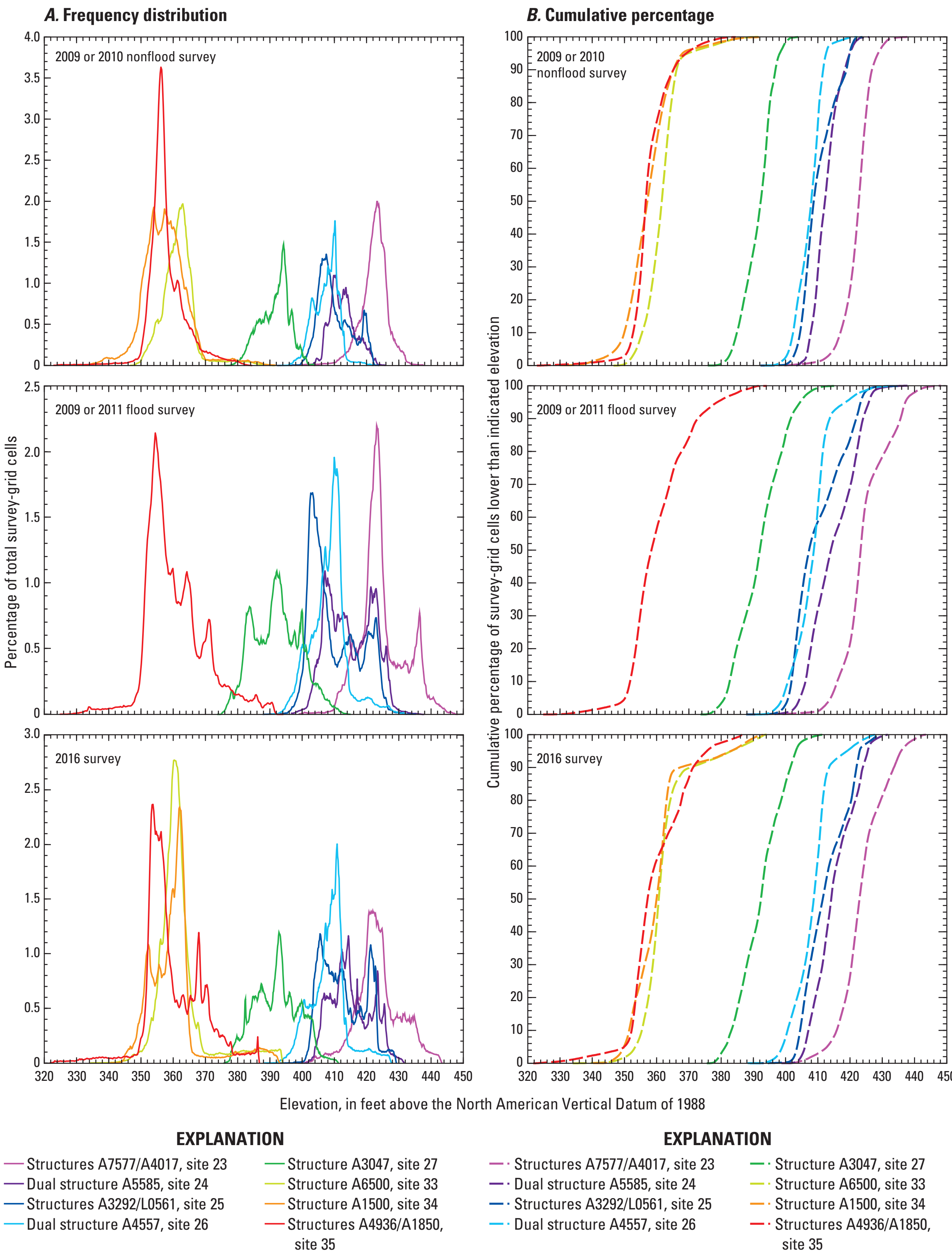


Figure 61. Comparison of frequency distribution and cumulative percentage of bed elevations for bathymetric survey-grid cells from various surveys on the Missouri and Mississippi Rivers near St. Louis, Missouri. *A*, frequency distribution. *B*, cumulative percentage.

A longitudinal profile was drawn upstream from the nose of each pier with a well-defined scour hole, and the approximate frontal slope (computed as horizontal distance over vertical distance, or run over rise, for relatability to highway embankment slopes) was determined for each hole (tables 6, 8). The frontal slope was not determined for piers with poorly defined scour holes. Profiles for selected piers are shown in figures 62 through 64.

The approximate frontal slope of the well-defined scour holes for sites on the Missouri River ranged from 1.06 to 3.03 (figs. 62, 63; table 6). Several scour holes at the Missouri River sites had frontal slopes of values greater than 3.03, but generally scour holes near these piers were substantially affected by an upstream pier (table 6). The approximate frontal slope of the well-defined scour holes for sites on the Mississippi River ranged from 1.28 to 2.27 (fig. 64; table 8). The mean value of the frontal slopes at the Missouri River sites not affected by upstream piers was 2.09 (table 6), and the mean value at the Mississippi River sites was 1.79 (table 8). Richardson and Davis (2001) noted that the side slope of a scour hole in cohesionless sand in air could range from 1.0 to 1.8 depending on the composition of the bed material and its dry angle of repose, and suggest using a value of 2.0 for design purposes to account for the wet angle of repose. The slope values determined in the current (2016) study generally are similar to the values noted in Richardson and Davis (2001) and to values determined for scour holes in similar studies (Huizinga, 2010, 2011, 2015, 2016), and are similar to previous surveys at these sites (figs. 62–64).

A longitudinal profile also was drawn upstream from the nose of the railroad bridge piers near dual bridge structure A4557 and near structure A3047, and the approximate frontal slope was determined for each hole (fig. 65). Although analysis of scour near the railroad bridges was not within the scope of the study, these railroad bridges were in close proximity to the highway bridges, and fell within the boundaries of the survey at these highway bridge sites. The approximate frontal slope of the well-defined scour holes at the railroad bridge piers ranged from 1.67 to 3.39 (fig. 65); however, the hole with the largest slope value—or the shallowest frontal slope—(3.39 at the right main channel pier of the Wabash railroad bridge; figs. 27, 65*B*) was observed in an area with a nearly planar bed with low velocities (fig. 29), which indicate minimal sediment transport in that area. Piers in similar planar bed areas near dual bridge structure A5585 (pier 7 of both eastbound and westbound bridges; fig. 13) also demonstrated very shallow frontal slopes (figs. 62*H*, 62*K*; table 6).

Several of the surveyed bridges had piers that were skewed to approach flow, resulting in asymmetric scour holes at those bridges: bents 7 and 8 of structure A7577 and pier 5 of structure A4017 on U.S. Highway 40 (fig. 6); pier 15 of structure A3292 and pier 16 of structure L0561 on Interstate 70 (fig. 20); pier 3C of dual bridge structure A4557 on State Highway 370 (fig. 27); pier 11 of structure A6500 on Interstate 70 (fig. 40); and pier 12 of structures A4936 and A1850 on Interstate 255 (fig. 51). Generally, the scour hole was longer on the side of the pier with impinging flow, with some amount of deposition on the leeward side, as typically has been observed at piers skewed to approach flow; however, at most of the skewed piers in the current (2016) study, the scour hole was deeper on the leeward side of the pier (see bent 7, structure A7577 [fig. 6]; pier 15, structure A3292 [fig. 20]; downstream pier 3C, structure A4557 [fig. 27]; and pier 11, structure A6500 [fig. 40]). At most of these piers, the angled approach flow was the result of a deflection or contraction of flow caused by a spur dike near the pier (figs. 6, 20, 27), which may affect flow differently than for a simple skew. At structure A6500, the very wide face of the pier footing and seal course (over 55 ft) would behave as a complex foundation, for which scour is computed differently (Richardson and Davis, 2001). At all of the structures, the skew to approach flow is apparent in the velocity vectors (figs. 12, 22, 29, 45, 55).

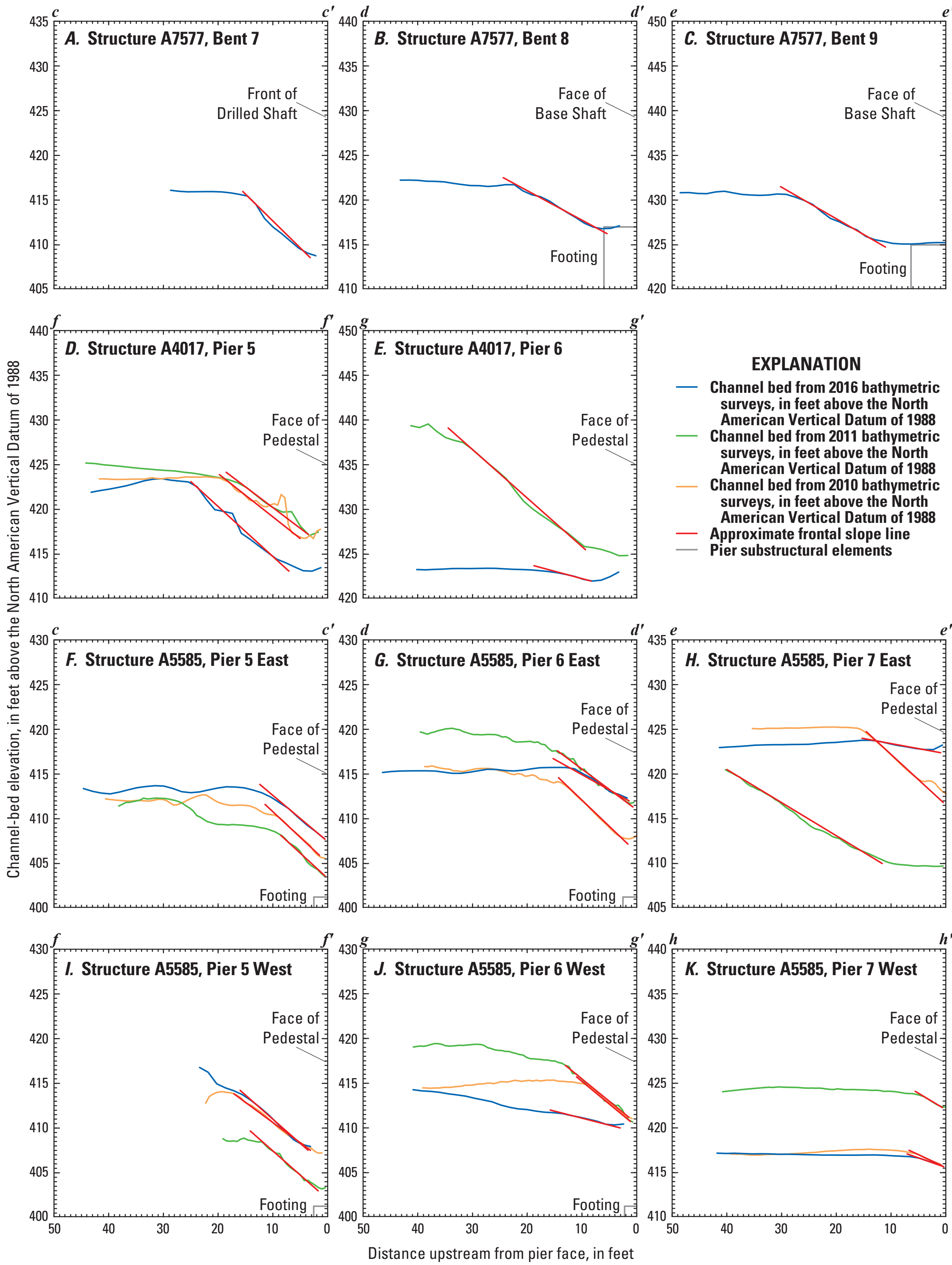


Figure 62. Longitudinal profiles upstream from selected piers at structures A7577 and A4017 on U.S. Highway 40, and at dual bridge structure A5585 on State Highway 364, crossing the Missouri River near St. Louis, Missouri

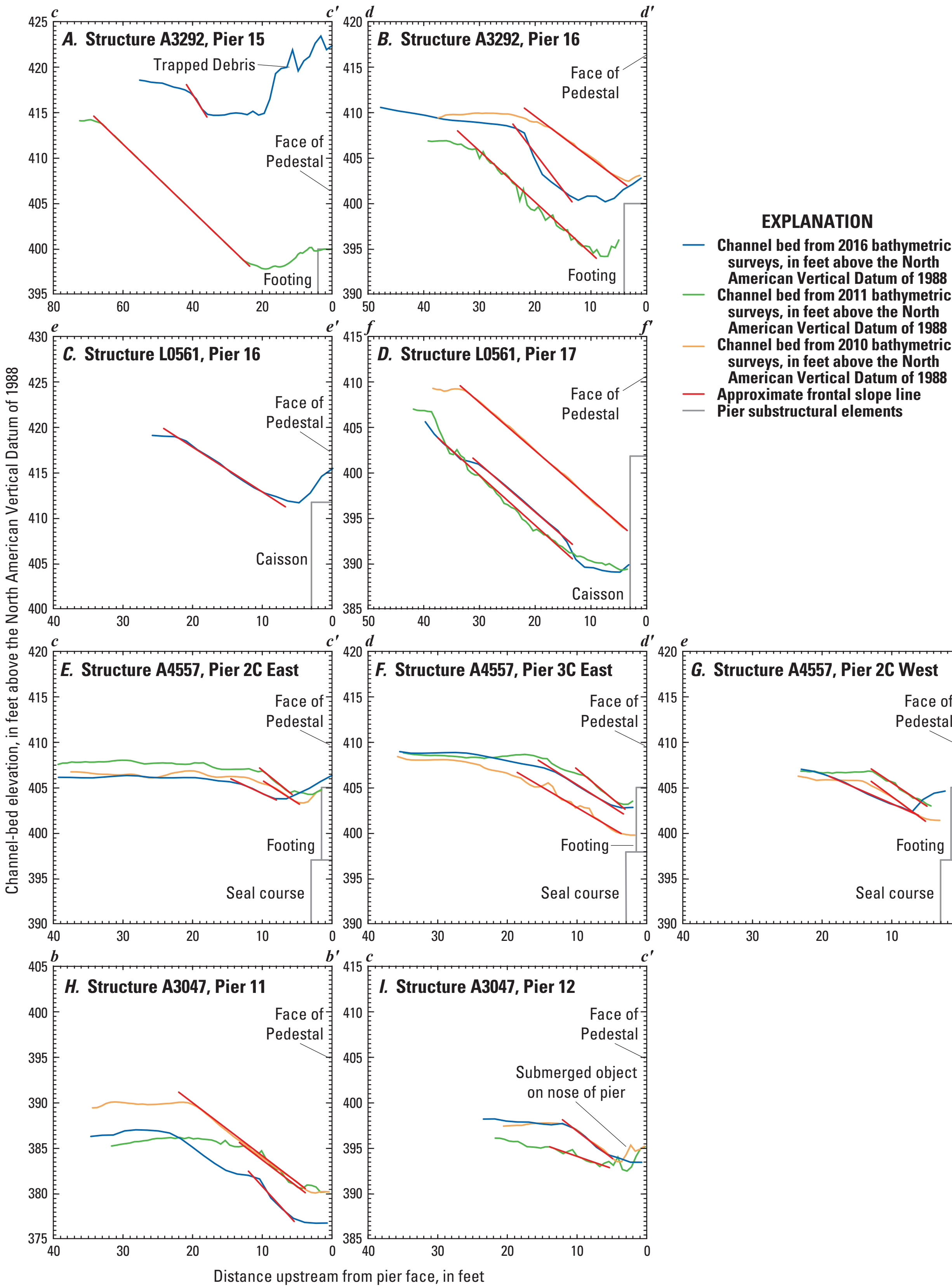


Figure 63. Longitudinal profiles upstream from selected piers at structures A3292 and L0561 on Interstate 70, at dual bridge structure A4557 on State Highway 370, and at structure A3047 on U.S. Highway 67, crossing the Missouri River near St. Louis, Missouri.

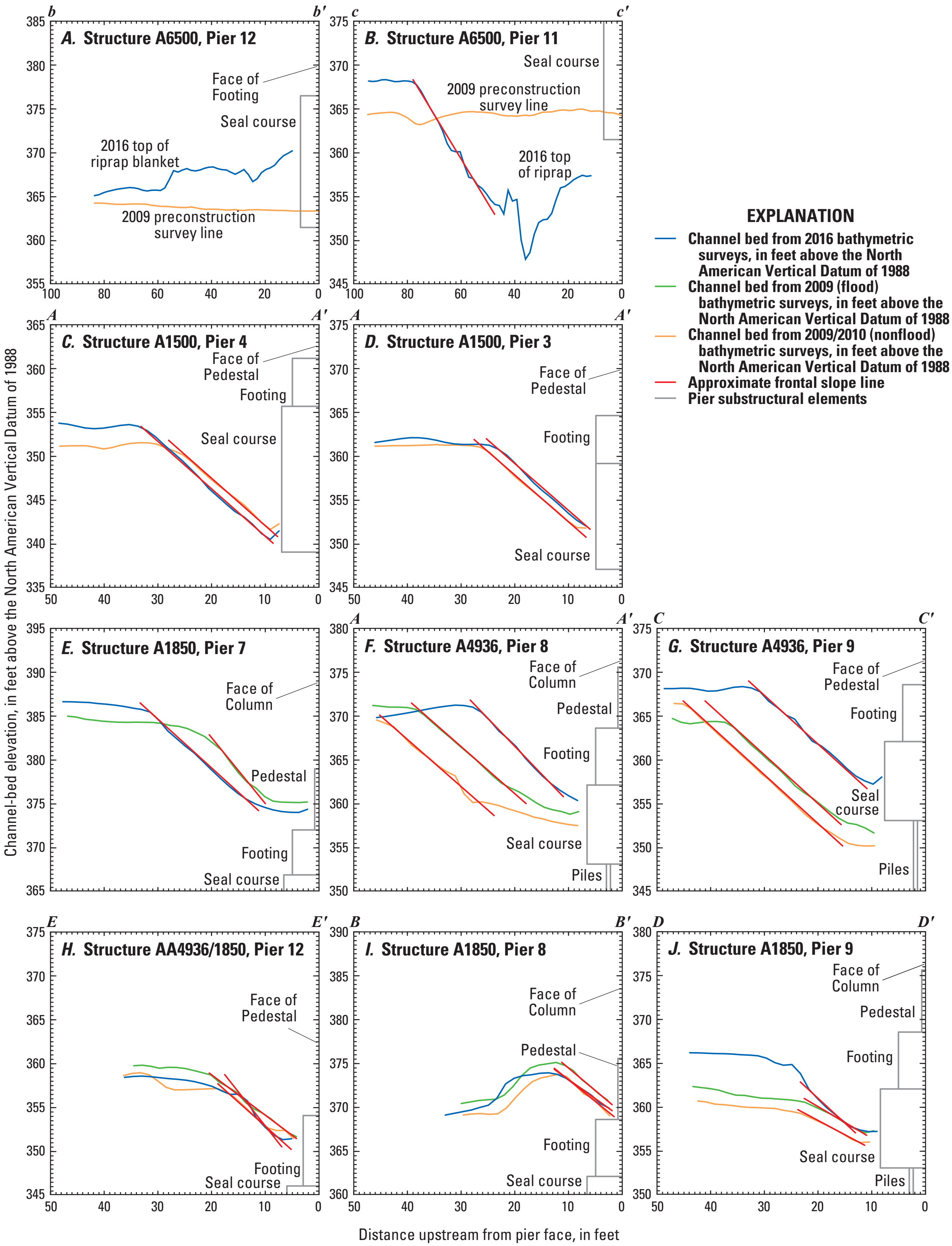


Figure 64. Longitudinal profiles upstream from selected piers at structure A6500 on Interstate 70, at structure A1500 on Interstate 55, and at structures A4936 and A1850 on Interstate 255, crossing the Mississippi River near St. Louis, Missouri.

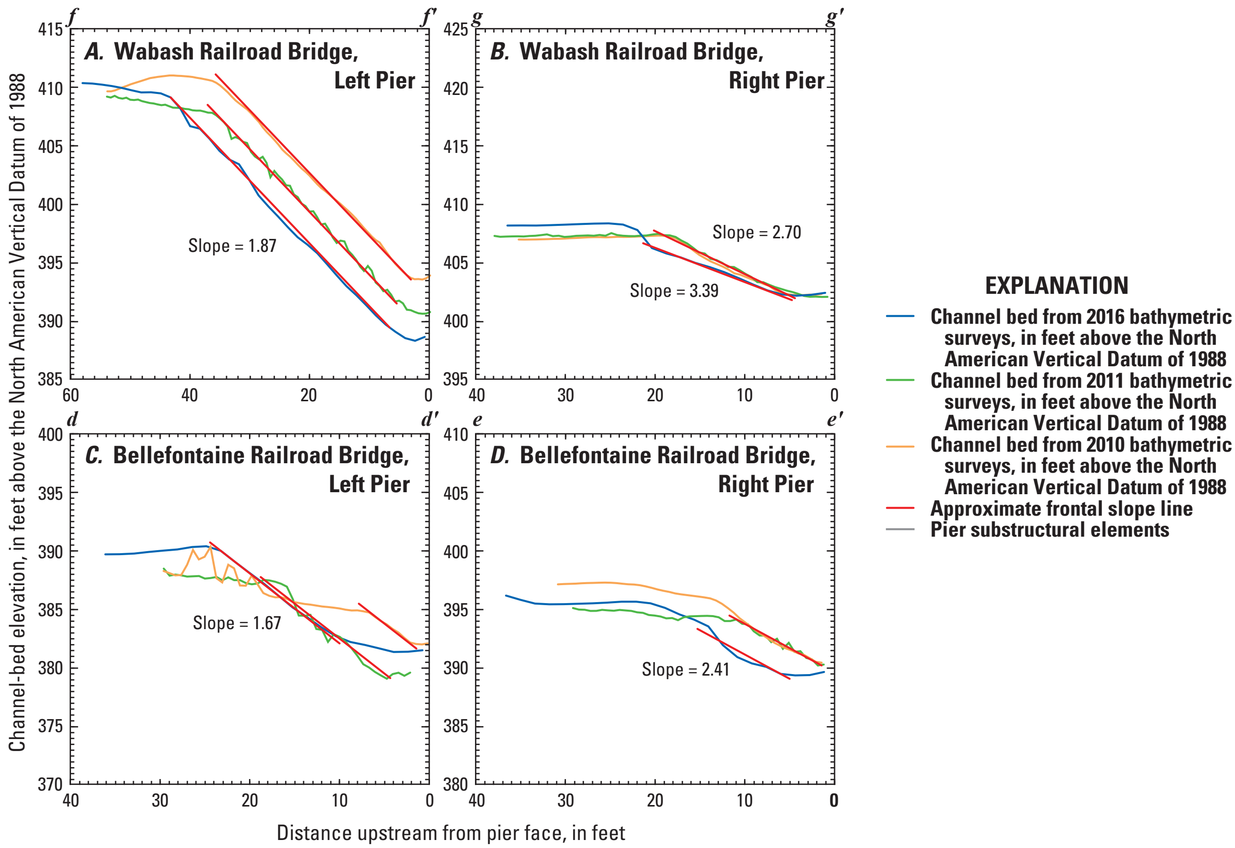


Figure 65. Longitudinal profiles upstream from railroad bridge piers near dual bridge structure A4557 on State Highway 370, and near structure A3047 on U.S. Highway 67, crossing the Missouri River near St. Louis, Missouri.

Summary and Conclusions

Bathymetric and velocimetric data were collected on the Missouri and Mississippi River near 13 highway bridges at 8 crossings in the greater St. Louis, Mo., area by the U.S. Geological Survey in cooperation with the Missouri Department of Transportation. A multibeam echosounder mapping system was used to obtain channel-bed elevations for areas ranging from 1,640 to 1,970 feet longitudinally and generally extending across the active channel from bank to bank in the Missouri and Mississippi Rivers during low to moderate flood flow conditions. These surveys document the channel-bed conditions and velocity distribution at the time of the surveys and provide characteristics of scour holes that may be useful in the development of predictive guidelines or equations for scour holes. These data also may be used by the Missouri Department of Transportation as a moderate flow comparison to help assess the bridges for stability and integrity issues with respect to bridge scour during floods.

The estimated total propagated uncertainty for the bathymetric surface of each survey area was computed as an estimate of the accuracy to be expected for each point with all relevant error sources taken into account. An analysis of the surveys indicated that more than 97 percent of the bathymetric data at all the sites have a total propagated uncertainty of less than 0.50 feet, and over three-quarters (78 percent or more) of the channel-bed elevations at the sites have a total propagated uncertainty of 0.25 feet or less.

At all the surveyed bridges, a variety of fluvial features were detected in the channel ranging from small ripples to large dunes that indicate moderate transport of bedload. Two sites had areas of a planar or nearly-planar bed, indicating minimal sediment transport in these areas. Rock outcrops also were detected along one bank at several sites where the alluvial material of the channel bed had been washed away.

Bathymetric data were collected around every pier that was in water, except those at the edge of water, and scour holes were observed at most surveyed piers. The observed scour holes at the surveyed bridges were examined with respect to shape and depth.

At structure A6500 at Interstate 70 crossing the Mississippi River, the previous survey was part of a habitat assessment before construction of the bridge, which gives unique insight into the effects of the construction of structure A6500 on the channel in this reach. Although the discharge and water-surface elevation for the survey on May 25, 2016, were similar to during the preconstruction survey on July 7, 2009, the difference between the bathymetric surfaces from each survey indicated moderate scour overall in the reach from 2009 to 2016, with an average difference of –1.36 ft between the bathymetric surfaces. Substantial scour of nearly 30 feet was observed at and downstream from pier 11. Both piers are skewed to approach flow, and the scour hole near pier 11 has the typical characteristics of a hole at a skewed pier, being longer on the side with impinging flow, and with a line of deposition on the leeward side. However, the wide, square nose of the pier, a mild constriction downstream from the pier, and additional scour from adjacent mooring dolphins downstream likely have exacerbated the scour on the leeward side of the pier by increasing local turbulence and pulling sediment into suspension. A riprap blanket surrounds pier 12, and seems to limit scour near that pier.

Flow rates at the Missouri River sites (sites 23 to 27) during the 2016 surveys ranged from about 20 to 50 percent greater than the 2010 flow rate, and water-surface elevations were 1.5 to 3.5 feet higher in 2016 than in 2010. Alternatively, flow rate at the Missouri River sites during the 2016 surveys ranged from about 49 to 58 percent of the 2011 flow rate, and water-surface elevations were about 7 to 9 feet lower in 2016 than in 2011. The average difference between the bathymetric surfaces varied from 1.8 feet lower to 0.9 feet higher in 2016 than 2010, and varied from 0.3 feet lower to 2.2 feet higher in 2016 than 2011. The average channel-bed elevation exhibits only small variation with time at the Missouri River sites, and generally, the average channel-bed elevation of the 2016 surveys fell between the two previous surveys, as might be expected given the discharge ratios of the 2016 compared to the previous surveys. However, the lack of variability in the average channel-bed elevations at dual bridge structure A4557 (site 26) and structure A3047 (site 27) farther downstream may indicate these sites are at or near a local feature that controls sediment deposition and scour.

Flow rates at sites 34 and 35 on the Mississippi River during the 2016 surveys were less than 1 percent different than the 2010 flow rates, and about 6 percent lower than the 2009 flow rate at site 33; water-surface elevations were about 1 to 2 feet lower in 2016 than in the previous survey. The average difference between the bathymetric surfaces varied from 1.4 feet lower to 0.8 feet higher in 2016 than the previous survey. The average channel-bed elevation exhibits more variation with time than the Missouri River sites, and generally, the average channel-bed elevation of the 2016 surveys fell above the previous survey, as might be expected given the discharge ratios of the 2016 compared to the previous survey.

The flow rate of the May 2009 survey at structures A4936 and A1850 (site 35) was high enough to be considered a “flood” survey, with the 2016 flow rate being about 68 percent of the May 2009 flow rate and similar in magnitude to the 2011 flood as measured at the streamgage at St. Charles, Mo. The water-surface elevation was over 13 feet lower in 2016 than in May 2009, but the average channel-bed elevation was only 0.2 feet lower in 2016 than in May 2009. The average difference between the bathymetric surfaces from all the various surveys at this site only ranged from 0.2 feet lower to 0.8 feet higher, regardless of the flow conditions.

The frontal slope values determined for scour holes observed in the current (2016) study generally are similar to recommended values in the literature and to values determined for scour holes in previous bathymetric surveys. Several of the structures had piers that were skewed to primary approach flow, and generally, the scour hole was longer on the side of the pier with impinging flow with some amount of deposition on the leeward side, as typically has been observed at piers skewed to approach flow; however, at a majority of the skewed piers in the current (2016) study, the scour hole was deeper on the leeward side of the pier. At most of these piers, the angled approach flow was the result of a deflection or contraction of flow caused by a spur dike near the pier, which may affect flow differently than for a simple skew. At structure A6500, the very wide face of the pier footing and seal course would behave as a complex foundation, for which scour is computed differently.

References Cited

Applanix Corporation, 2009, POS-Pac™ MMS™ GNSS-inertial tools user guide, rev. 4: Richmond Hill, Ontario, Canada, PUBS–MAN–001768, 523 p.

Calder, B.R., and Mayer, L.A., 2003, Automatic processing of high-rate, high-density multibeam echosounder data: Geochemistry, Geophysics, Geosystems (G^3), v. 4, no. 6, 22 p. [Also available at https://doi.org/10.1029/2002GC000486.]

Czuba, J.A., Best, J.L, Oberg, K.A., Parsons, D.R., Jackson, P.R., Garcia, M.H., and Ashmore, Peter, 2011, Bed morphology, flow structure, and sediment transport at the outlet of Lake Huron and in the Upper Saint Clair River: Journal of Great Lakes Research, v. 37, no. 3, p. 480–493. [Also available at https://doi.org/10.1016/j.jglr.2011.05.011.]

Densmore, B.K., Strauch, K.R., and Dietsch, B.J., 2013, Hydrographic surveys of the Missouri and Yellowstone Rivers at selected bridges and through Bismarck, North Dakota, during the 2011 flood: U.S. Geological Survey Scientific Investigations Report 2013–5087, 59 p. [Also available at https://pubs.usgs.gov/sir/2013/5087/.]

Dietsch, B.J., Densmore, B.K., and Strauch, K.R., 2014, Hydrographic surveys at selected highway bridges crossing the Missouri River using a multibeam echosounder, 2011: U.S. Geological Survey Scientific Investigations Report 2014–5062, 53 p. [Also available at https://doi.org/10.3133/sir20145062.]

Esri, 2013, ArcGIS: Environmental Systems Research Institute (Esri), accessed July 2013 at http://www.esri.com/software/arcgis/.

Gilbert, G.K., and Murphy, E.C., 1914, The transport of débris by running water: U.S. Geological Survey Professional Paper 86, 263 p. [Also available at https://pubs.er.usgs.gov/publication/pp86.]

Huizinga, R.J., 2010, Bathymetric surveys at highway bridges crossing the Missouri River in Kansas City, Missouri, using a multibeam echo sounder, 2010: U.S. Geological Survey Scientific Investigations Report 2010–5207, 61 p. [Also available at https://pubs.usgs.gov/sir/2010/5207/.]

Huizinga, R.J., 2011, Bathymetric surveys at highway bridges crossing the Missouri and Mississippi Rivers near St. Louis, Missouri, 2010: U.S. Geological Survey Scientific Investigations Report 2011–5170, 75 p. [Also available at https://pubs.usgs.gov/sir/2011/5170/.]

Huizinga, R.J., 2012, Bathymetric and velocimetric surveys at highway bridges crossing the Missouri River in and into Missouri during summer flooding, July–August 2011: U.S. Geological Survey Scientific Investigations Report 2012–5204, 166 p. [Also available at https://pubs.usgs.gov/sir/2012/5204/.]

Huizinga, R.J., 2013, Results of repeat bathymetric and velocimetric surveys at the Amelia Earhart Bridge on U.S. Highway 59 over the Missouri River at Atchison, Kansas, 2009–2013: U.S. Geological Survey Scientific Investigations Report 2013–5177, 50 p. [Also available at https://pubs.usgs.gov/sir/2013/5177.]

Huizinga, R.J., 2014, Bathymetric and velocimetric surveys at highway bridges crossing the Missouri River between Kansas City and St. Louis, Missouri, April–May, 2013: U.S. Geological Survey Scientific Investigations Report 2014–5116, 79 p. [Also available at https://doi.org/10.3133/sir20145116.]

Huizinga, R.J., 2015, Bathymetric and velocimetric surveys at highway bridges crossing the Missouri and Mississippi Rivers on the periphery of Missouri, June 2014: U.S. Geological Survey Scientific Investigations Report 2015–5048, 81 p. [Also available at https://doi.org/10.3133/sir20155048.]

Huizinga, R.J., 2016, Bathymetric and velocimetric surveys at highway bridges crossing the Missouri River near Kansas City, Missouri, June 2–4, 2015: U.S. Geological Survey Scientific Investigations Report 2016–5061, 93 p. [Also available at https://doi.org/10.3133/sir20165061.]

Huizinga, R.J., 2017, Bathymetry and velocity data from surveys at highway bridges crossing the Missouri and Mississippi Rivers near St. Louis, Missouri, October 2008 through May 2016: U.S. Geological Survey data release, https://doi.org/10.5066/F71C1VCC.

Huizinga, R.J., Elliott, C.M., and Jacobson, R.B., 2010, Bathymetric and velocimetric survey and assessment of habitat for pallid sturgeon on the Mississippi River in the vicinity of the proposed Interstate 70 Bridge at St. Louis, Missouri: U.S. Geological Survey Scientific Investigations Report 2010–5017, 28 p. [Also available at https://pubs.usgs.gov/sir/2010/5017/.]

Huizinga, R.J., and Rydlund, P.H., Jr., 2004, Potential-scour assessments and estimates of scour depth using different techniques at selected bridge sites in Missouri: U.S. Geological Survey Scientific Investigations Report 2004–5213, 42 p. [Also available at https://pubs.usgs.gov/sir/2004/5213/.]

HYPACK, Inc., 2015, HYPACK® hydrographic survey software user manual: Middletown, Conn., HYPACK, Inc., 2,041 p.

International Hydrographic Organization, 2008, IHO standards for hydrographic surveys (5th ed.): Monaco, International Hydrographic Bureau, Special publication No. 44, 27 p.

Lagasse, P.F., Shall, J.D., Johnson, F., Richardson, E.V., Richardson, J.R., and Chang, F., 1991, Stream stability at highway structures: U.S. Federal Highway Administration Publication FHWA–IP–90–014, Hydraulic Engineering Circular no. 20, 195 p.

Missouri Department of Conservation, 2017, Chain of Rocks hazard: Missouri River Water Trail: Missouri Department of Conservation, accessed April 2017 at https://missouririver-watertrail.org/safety/chain-rocks-hazard.

Mueller, D.S., Wagner, C.R., Rehmel, M.S., Oberg, K.A., and Rainville, Francois, 2013, Measuring discharge with acoustic Doppler current profilers from a moving boat (ver. 2.0, December 2013): U.S. Geological Survey Techniques and Methods, book 3, chap. A22, 95 p. [Also available at https://doi.org/10.3133/tm3A22.]

National Marine Electronics Association, 2002, NMEA 0183—Standard for interfacing marine electronic devices (ver. 3.01): National Marine Electronics Association, 88 p.

Parsons, D.R., Jackson, P.R., Czuba, J.A., Engel, F.L., Rhoads, B.L., Oberg, K.A., Best, J.L., Mueller, D.S., Johnson, K.K., and Riley, J.D., 2013, Velocity Mapping Toolbox (VMT)—A processing and visualization suite for moving-vessel ADCP measurements: Earth Surface Processes and Landforms, v. 38, no. 11, p. 1244–1260. [Also available at https://doi.org/10.1002/esp.3367.]

Richardson, E.V., and Davis, S.R., 2001, Evaluating scour at bridges (4th ed.): U.S. Federal Highway Administration Publication FHWA NHI 01–001, Hydraulic Engineering Circular no. 18, 378 p.

Rydlund, P.H., Jr., 2009, Real-time river channel-bed monitoring at the Chariton and Mississippi Rivers in Missouri, 2007–09: U.S. Geological Survey Scientific Investigations Report 2009–5254, 27 p. [Also available at https://pubs.usgs.gov/sir/2009/5254/.]

Simons, D.B., Richardson, E.V., and Nordin, C.F., Jr., 1965, Bedload equation for ripples and dunes: U.S. Geological Survey Professional Paper 462–H, 9 p. [Also available at https://pubs.er.usgs.gov/publication/pp462H.]

U.S. Army Corps of Engineers, 2003a, Upper Mississippi River System flow frequency study, appendix D: Rock Island, Ill., U.S. Army Corps of Engineers, accessed April 2017 at http://www.mvr.usace.army.mil/Portals/48/docs/FRM/UpperMissFlowFreq/App.%20D%20St.%20Louis%20Dist.%20Hydrology_Hydraulics.pdf.

U.S. Army Corps of Engineers, 2003b, Upper Mississippi River System flow frequency study, appendix E: Rock Island, Ill., U.S. Army Corps of Engineers, accessed April 2017 at http://www.mvr.usace.army.mil/Portals/48/docs/FRM/UpperMissFlowFreq/App.%20E%20Kansas%20City%20Dist.%20Hydrology_Hydraulics.pdf.

U.S. Army Corps of Engineers, 2013, Engineering and design—Hydrographic surveying: Washington D.C., U.S. Army Corps of Engineers, manual no. EM 1110–2–1003, 560 p.

U.S. Geological Survey, 2003, User's manual for the National Water Information System of the U.S. Geological Survey—Automated Data Processing System (ADAPS): U.S. Geological Survey Open-File Report 2003–123, 413 p., accessed September 2010 at https://pubs.usgs.gov/of/2003/ofr03123/.

U.S. Geological Survey, 2017, National Water Information System: U.S. Geological Survey database, accessed April 2017 at https://doi.org/10.5066/F7P55KJN.

Appendix 1. Shaded Triangulated Irregular Network Images of the Channel and Side of Pier for Each Surveyed Pier

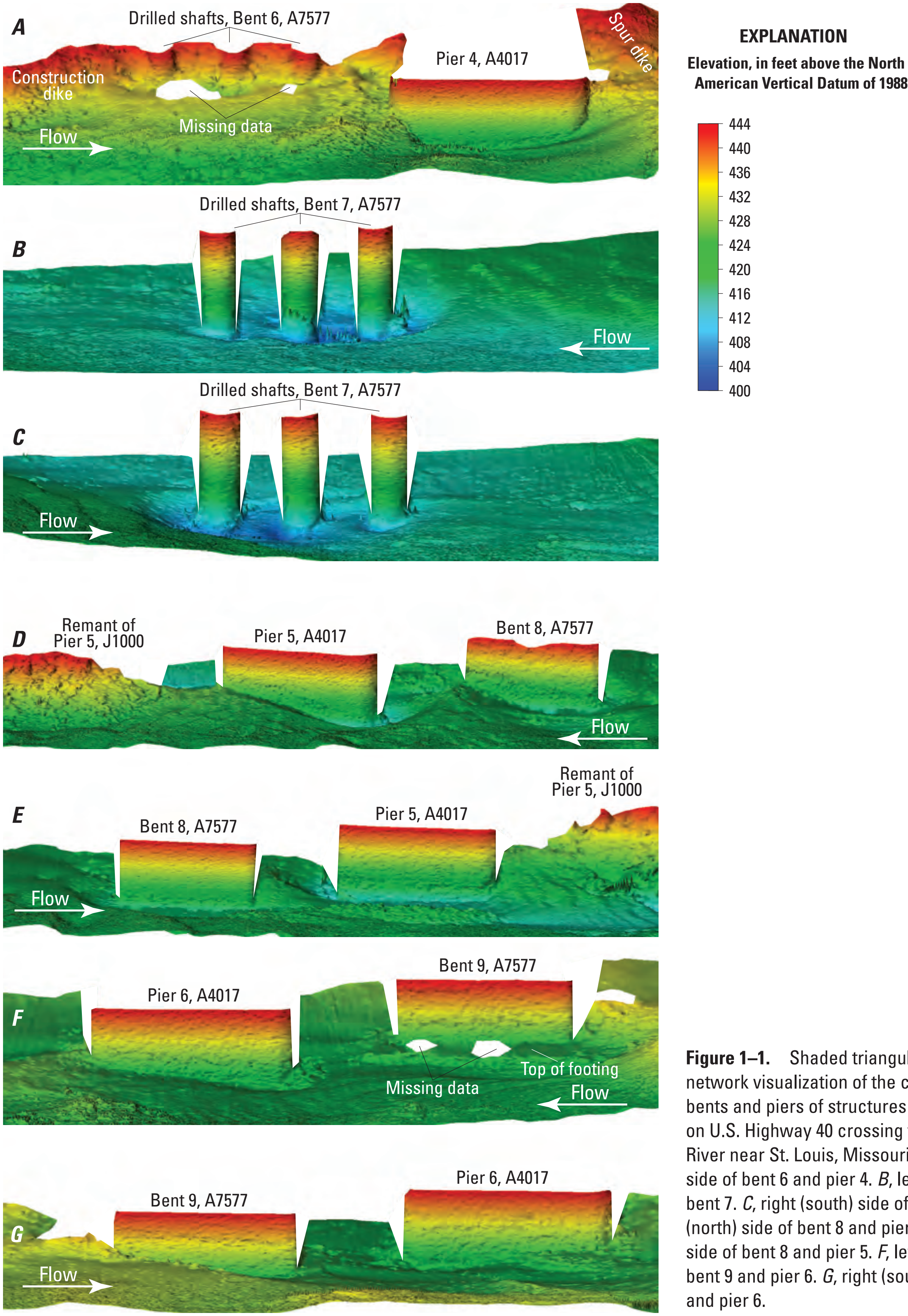


Figure 1–1. Shaded triangulated irregular network visualization of the channel bed and bents and piers of structures A7577 and A4017 on U.S. Highway 40 crossing the Missouri River near St. Louis, Missouri. *A*, right (south) side of bent 6 and pier 4. *B*, left (north) side of bent 7. *C*, right (south) side of bent 7. *D*, left (north) side of bent 8 and pier 5. *E*, right (south) side of bent 8 and pier 5. *F*, left (north) side of bent 9 and pier 6. *G*, right (south) side of bent 9 and pier 6.

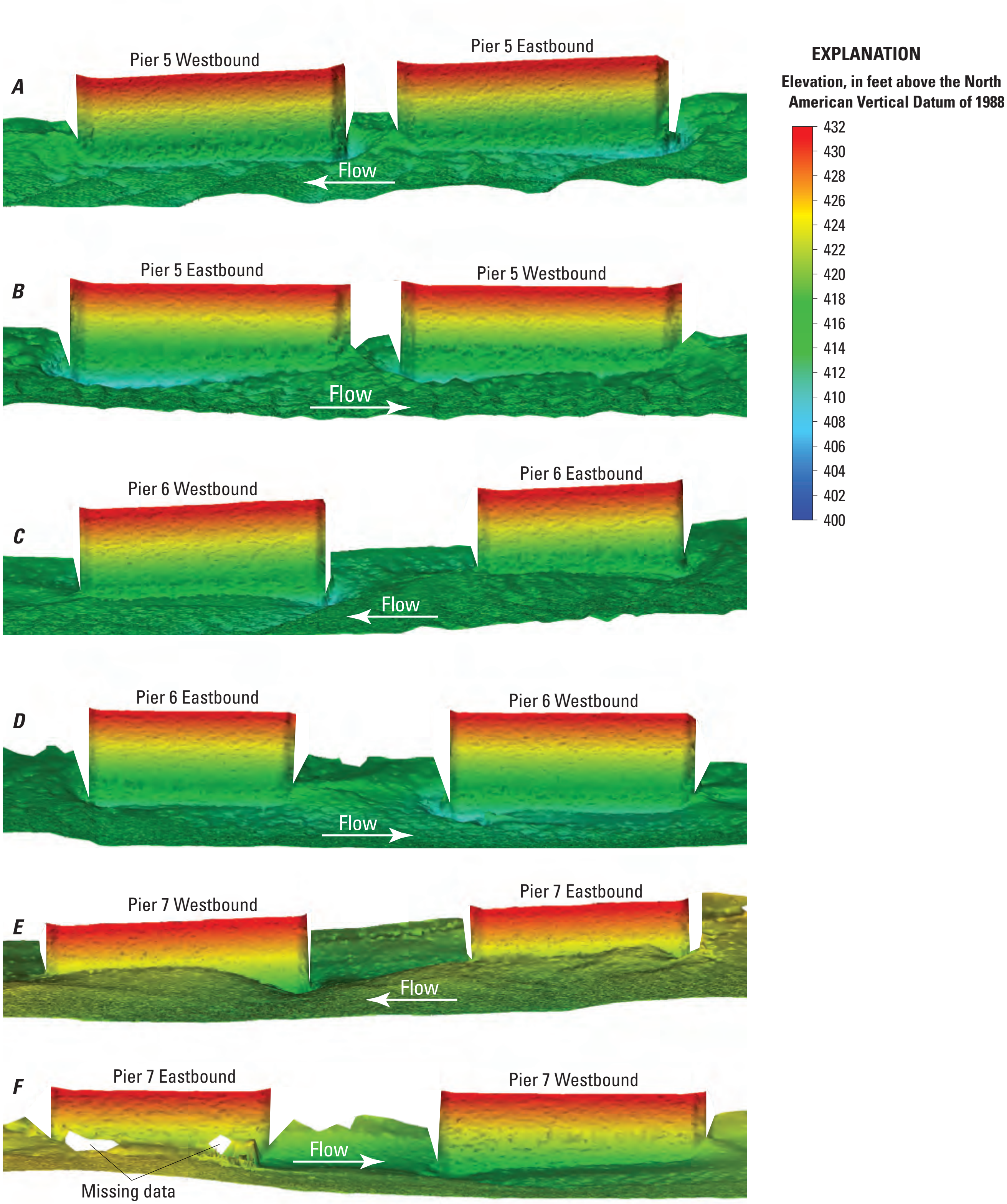


Figure 1–2. Shaded triangulated irregular network visualization of the channel bed and piers of dual bridge structure A5585 on State Highway 364 crossing the Missouri River near St. Louis, Missouri. *A*, left (north) side of pier 5. *B*, right (south) side of pier 5. *C*, left (north) side of pier 6. *D*, right (south) side of pier 6. *E*, left (north) side of pier 7. *F*, right (south) side of pier 7.

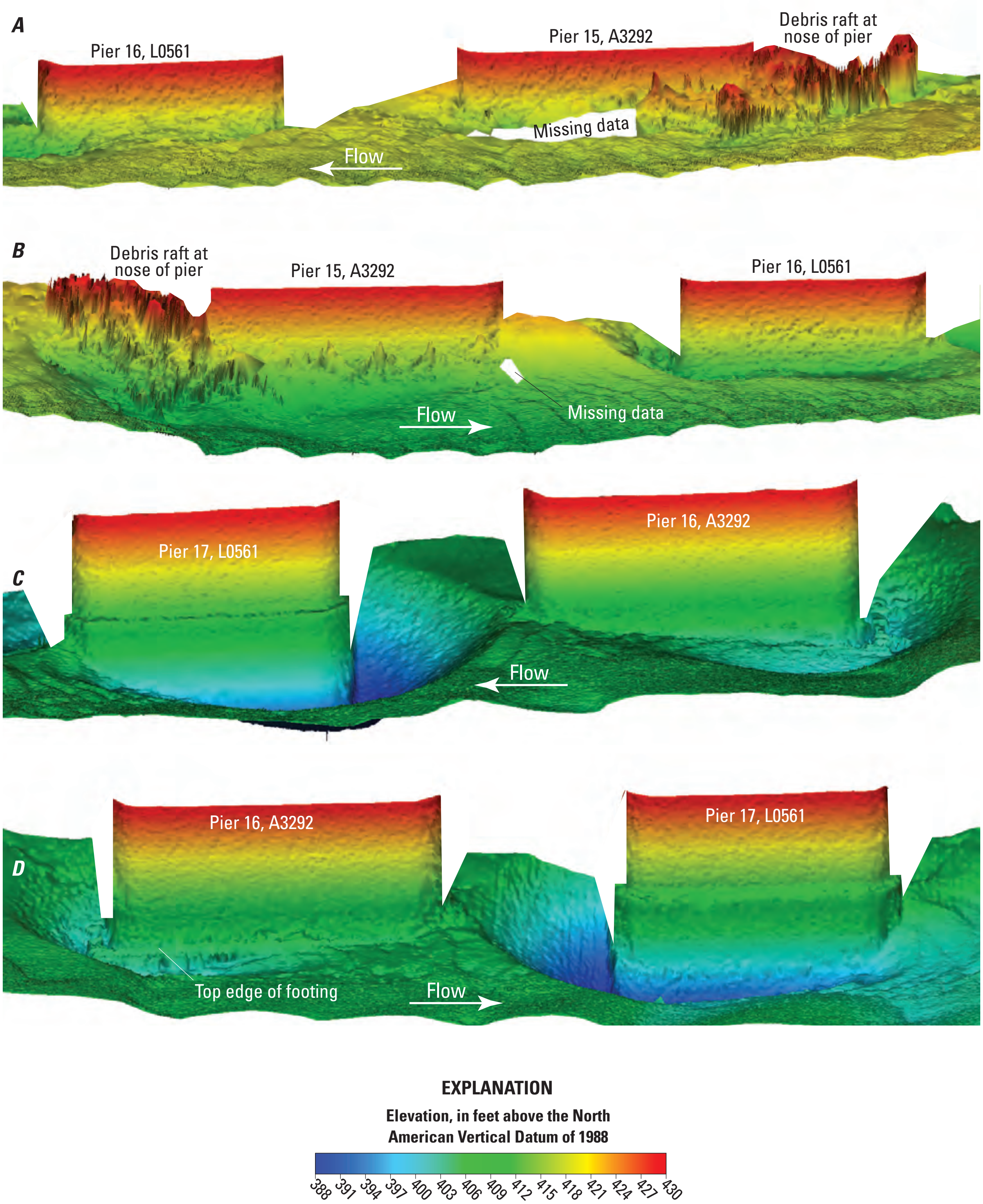


Figure 1–3. Shaded triangulated irregular network visualization of the channel bed and piers of structures A3292 and L0561 on Interstate 70 crossing the Missouri River near St. Louis, Missouri. *A*, left (northwest) side of piers 15 and 16. *B*, right (southeast) side of piers 15 and 16. *C*, left (northwest) side of piers 16 and 17. *D*, right (southeast) side of piers 16 and 17.

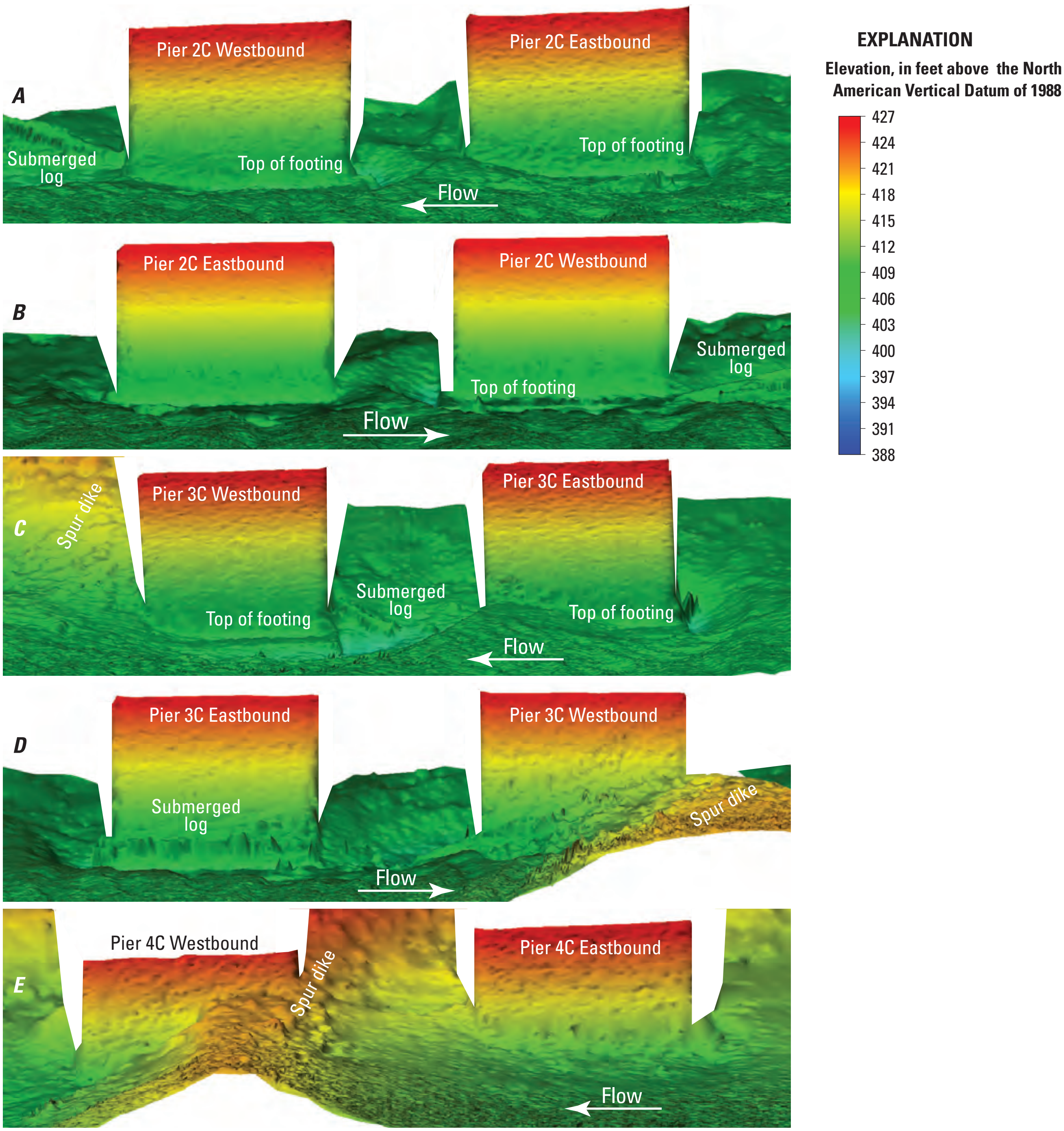


Figure 1–4. Shaded triangulated irregular network visualization of the channel bed and piers of dual bridge structure A4557 on State Highway 370 crossing the Missouri River near St. Louis, Missouri. *A*, left (northwest) side of pier 2C. *B*, right (southeast) side of pier 2C. *C*, left (northwest) side of pier 3C. *D*, right (southeast) side of pier 3C. *E*, left (northwest) side of pier 4C.

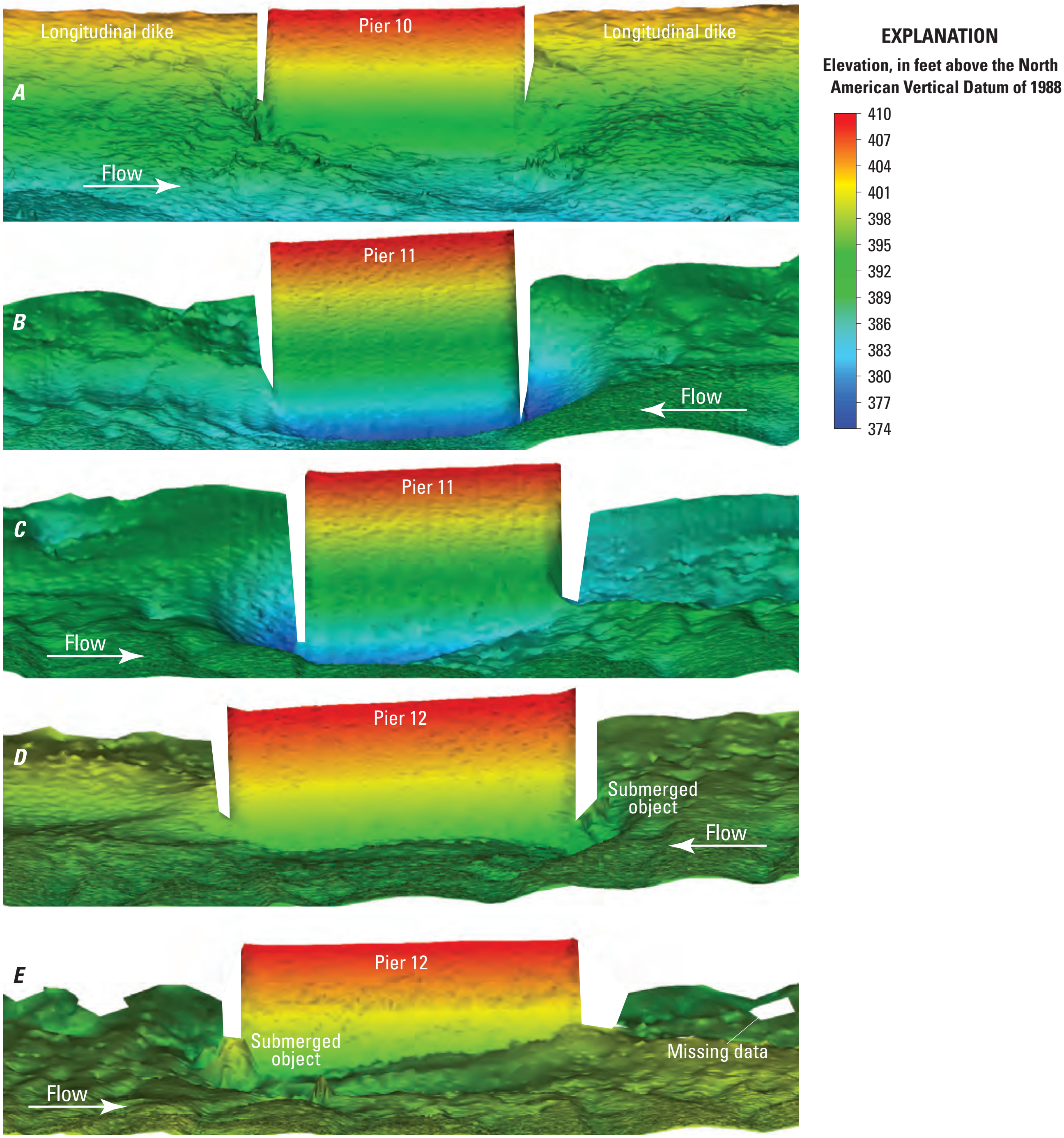


Figure 1–5. Shaded triangulated irregular network visualization of the channel bed and piers of structure A3047 on U.S. Highway 67 crossing the Missouri River near St. Louis, Missouri. *A*, right (south) side of pier 10. *B*, left (north) side of pier 11. *C*, right (south) side of pier 11. *D*, left (north) side of pier 12. *E*, right (south) side of pier 12.

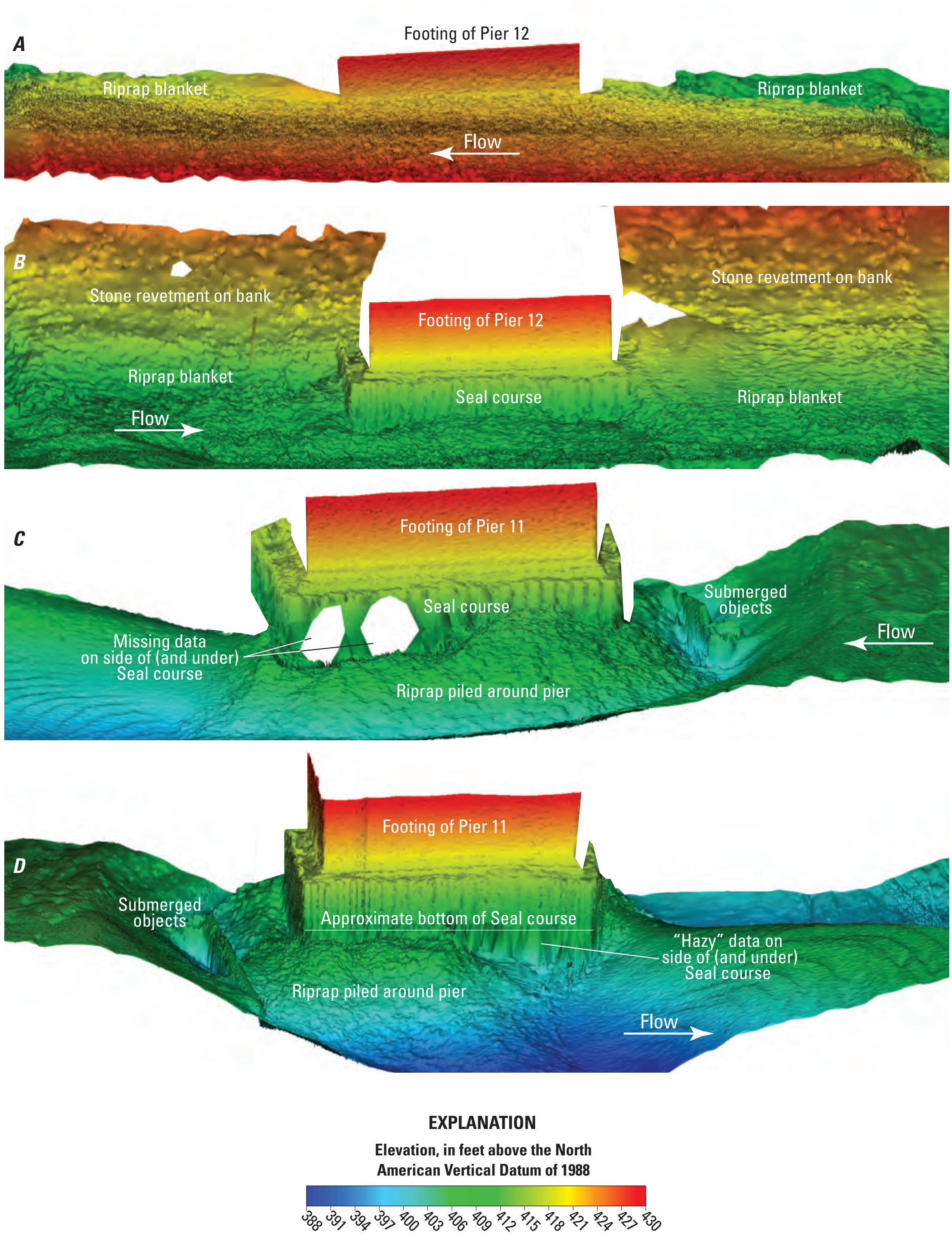
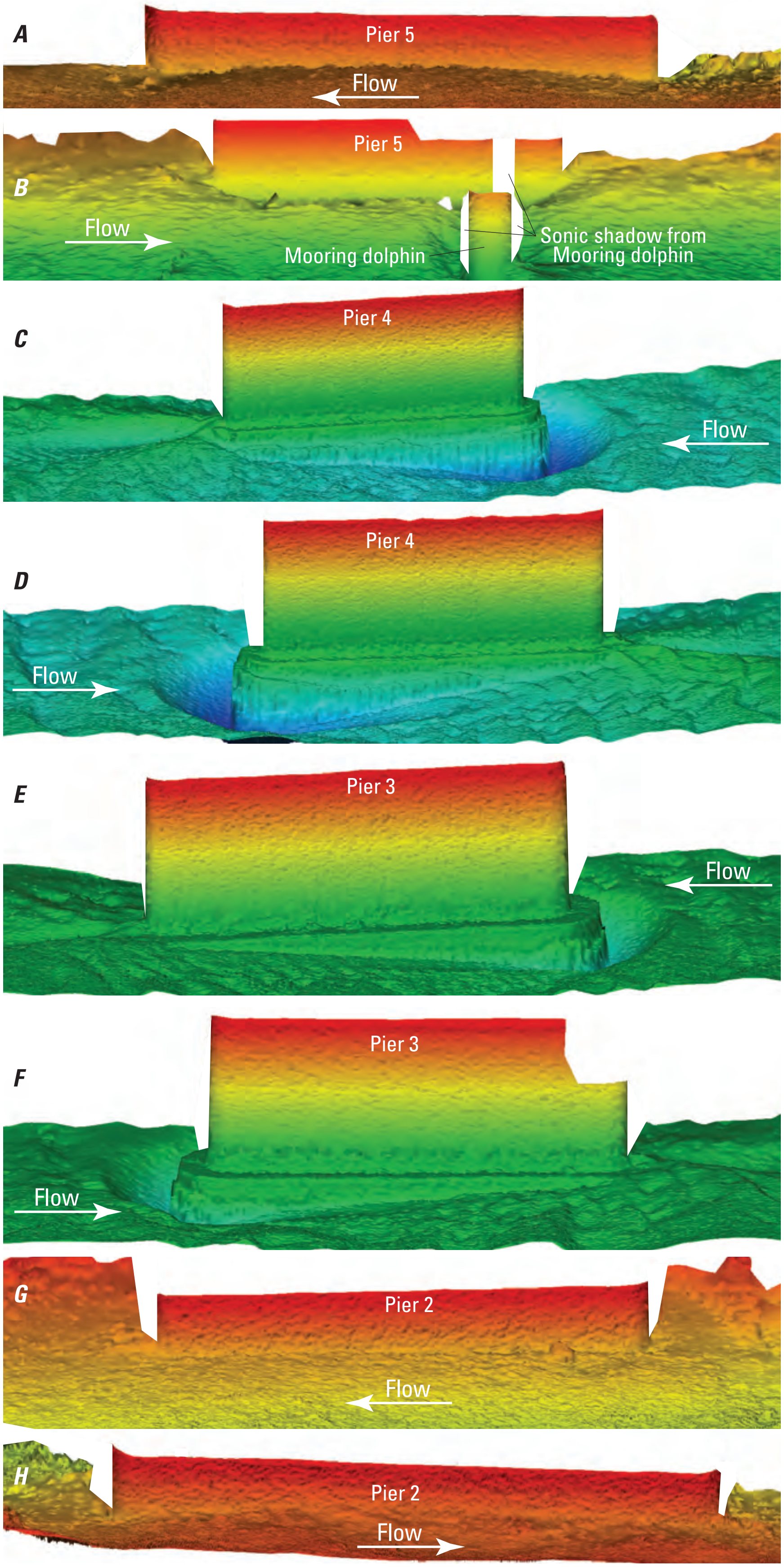


Figure 1–6. Shaded triangulated irregular network visualization of the channel bed and piers of structure A6500 on Interstate 70 crossing the Mississippi River in St. Louis, Missouri. *A*, left (east) side of pier 12. *B*, right (west) side of pier 12. *C*, left (east) side of pier 11. *D*, right (west) side of pier 11.



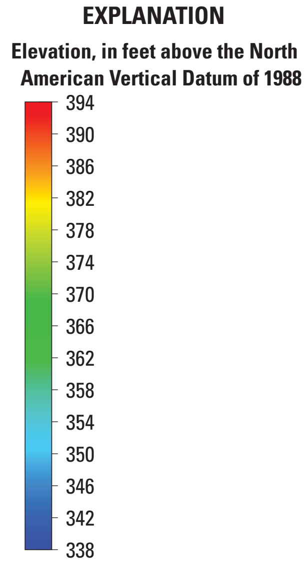


Figure 1–7. Shaded triangulated irregular network visualization of the channel bed piers of structure A1500 on Interstate 55 over the Mississippi River in St. Louis, Missouri. *A*, left (east) side of pier 5. *B*, right (west) side of pier 5. *C*, left (east) side of pier 4. *D*, right (west) side of pier 4. *E*, left (east) side of pier 3. *F*, right (west) side of pier 3. *G*, left (east) side of pier 2. *H*, right (west) side of pier 2.

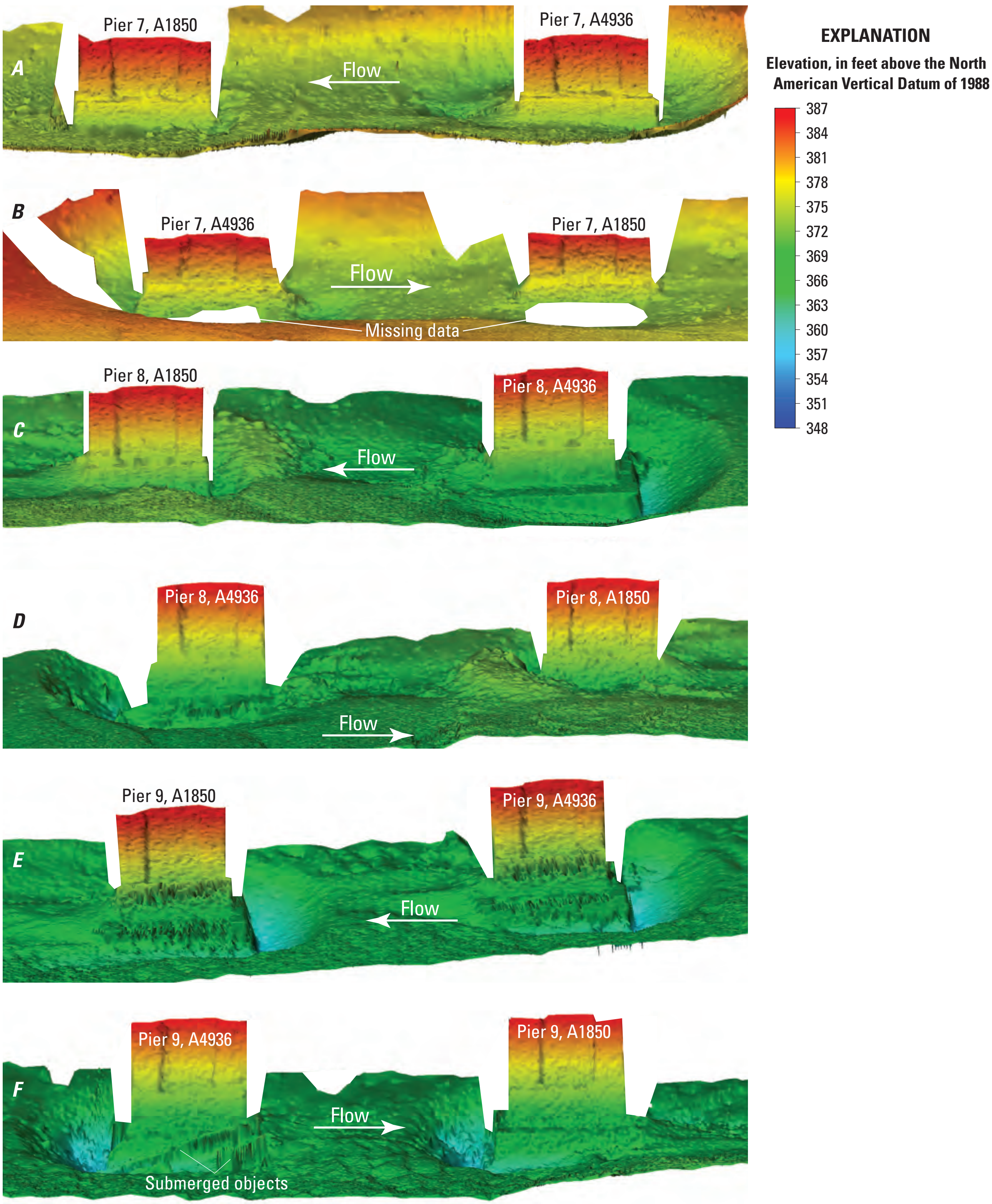


Figure 1–8. Shaded triangulated irregular network visualization of the channel bed and piers of structures A4936 and A1850 on Interstate 255 crossing the Mississippi River near St. Louis, Missouri. *A*, left (east) side of pier 7. *B*, right (west) side of pier 7. *C*, left (east) side of pier 8. *D*, right (west) side of pier 8. *E*, left (east) side of pier 9. *F*, right (west) side of pier 9.

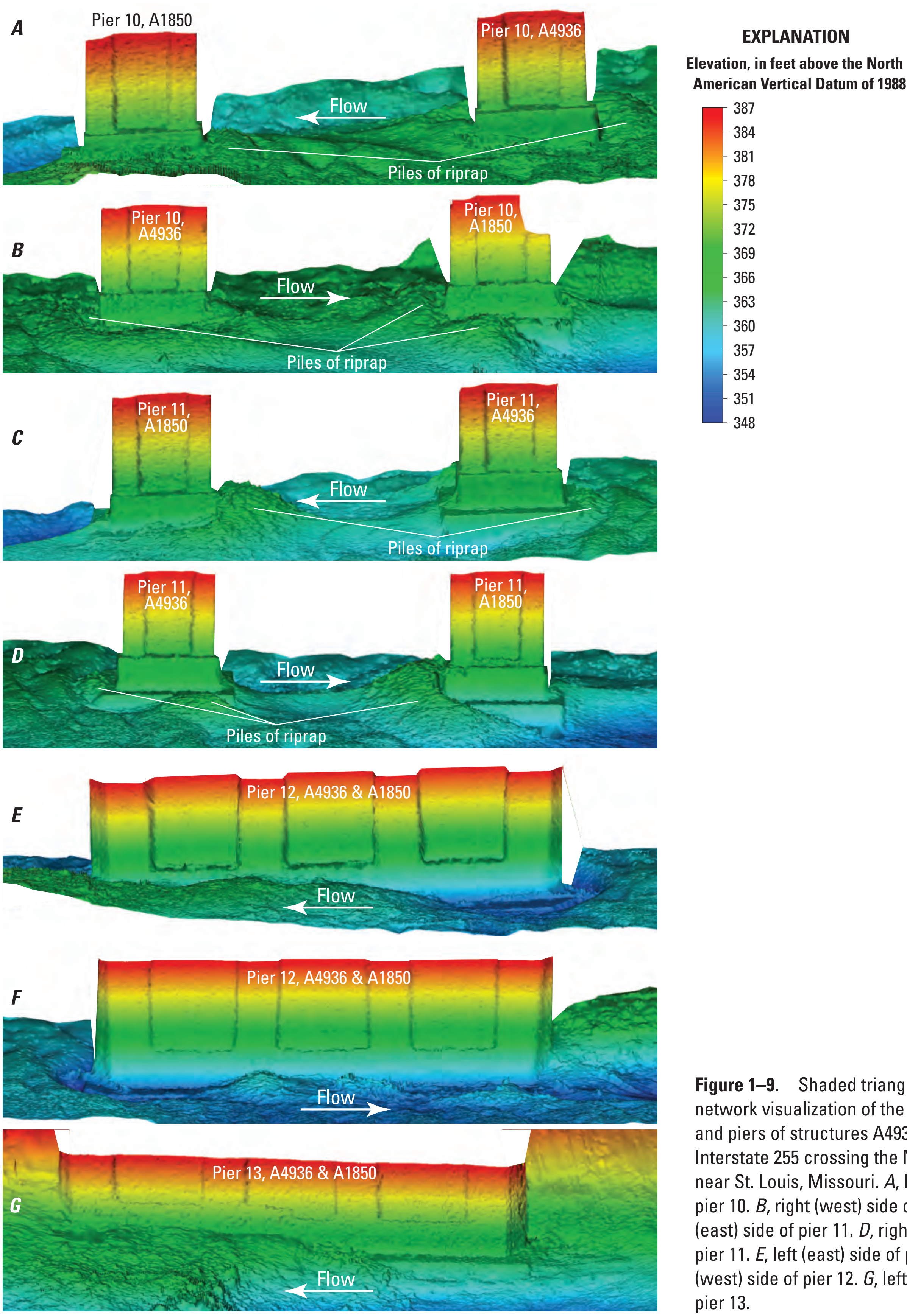


Figure 1–9. Shaded triangulated irregular network visualization of the channel bed and piers of structures A4936 and A1850 on Interstate 255 crossing the Mississippi River near St. Louis, Missouri. *A*, left (east) side of pier 10. *B*, right (west) side of pier 10. *C*, left (east) side of pier 11. *D*, right (west) side of pier 11. *E*, left (east) side of pier 12. *F*, right (west) side of pier 12. *G*, left (east) side of pier 13.

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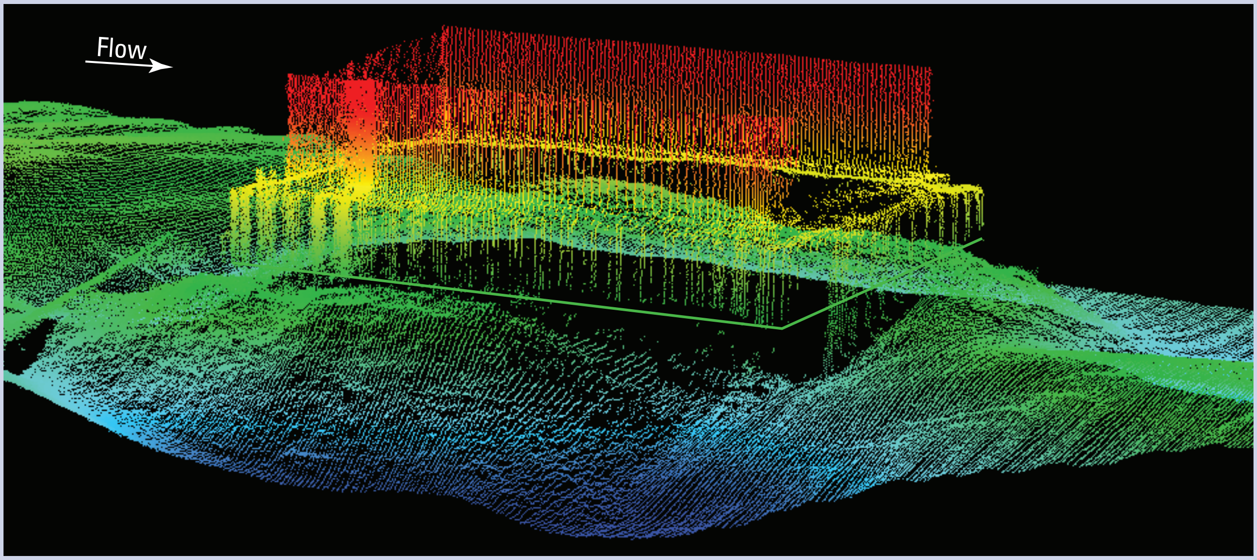
Huizinga—**Bathymetric and Velocimetric Surveys at Highway Bridges Crossing the Missouri and Mississippi Rivers near St. Louis, MO**—SIR 2017–5076



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