High-Resolution Multibeam Surveys for Bridge Assessment

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Though it has not been a widely used technique within the general bridge engineering community, multibeam surveying has begun to find a role in a few specific bridge-related applications. In recent years, multibeam surveying has been used as an assessment tool for periodic underwater bridge inspections and also to meet pre- and post-construction design and planning requirements in support of new bridge construction. Though there are tens of thousands of highway and railroad bridges over water in the United States, only a relatively small subset of these bridges occur in environments where multibeam surveying might be considered as an applicable technique. However, in areas with certain environmental characteristics (e.g., deep water, complex bottom topography, limited visibility, strong currents, etc.) multibeam surveying offers a number of unique benefits relative to other assessment techniques. This paper will provide an overview of multibeam surveying, as well as other acoustic bridge monitoring techniques, and then present a discussion on specific bridge-related multibeam applications.

MULTIBEAM ECHOSOUNDING

The use of shallow-water multibeam technology to provide accurate, high-resolution, full-bottom coverage seafloor topography has grown steadily over the last fifteen years. These systems are now relatively widely employed within both the public and commercial sector and are used to address many different inshore hydrographic survey requirements (e.g., nautical charting, dredging, coastal structure assessment, etc.). The acquisition and processing of multibeam bathymetric data is far more complex than comparable single-beam operations, and requires personnel who are experienced and well-trained in the techniques. At a minimum, multibeam operations require a multibeam echosounder, an accurate navigation device, a vessel motion sensor (for precisely and rapidly measurement of boat heave, pitch, and roll), an accurate heading source (e.g., gyrocompass, etc.), and an accurate measure of the water-column speed of sound. Although the multibeam systems are frequently installed on a semi-permanent basis on a designated survey vessel, multibeam systems can also be temporarily mounted on a vessel of opportunity. Because of the additional sensors required and the complexity of the relationship between these sensors, a temporary multibeam installation is significantly more complex than a comparable single-beam installation.

In addition to greatly enhancing the spatial resolution and density of depth measurements and the ability to detect small seafloor features, the expanded swath coverage will generally allow for wider survey lane spacing and may decrease survey time when compared to even a relatively sparse single-beam survey. Multibeam systems are capable of providing a total swath coverage that varies from 2 to 7 times the water depth, based on an overall array beam opening that might vary from 90° to 160° with a fixed-angle beam pattern of 0.5° to 3°. With a fixed-angle beam pattern the near nadir areas are ensonified by far more beams that provide much higher resolutions than the outer beam areas. In addition, because the outer beams are far more affected by a variety of potential error sources (e.g., roll and yaw biases, refraction, etc.), it is relatively common to restrict the use of the multibeam data to the inner 90° to 120°, thereby reducing the effective swath coverage.

Some newer multibeam systems provide enhanced beam-forming capability, and allow flexibility in both the overall array beam opening and the distribution of beams across that opening. For instance, with the R2Sonic 2024 multibeam echosounder the overall beam opening is user adjustable from 10° to 160°, with all 256 beams focused within the selected opening angle. In addition, the individual beams can be formed based on either an equal-angle or equal-distance preference. The equal-distance mode enables the individual beam angles to be varied across the opening to provide consistent spacing of the beam footprints across the seafloor. As opposed to the more standard equal-angle beam pattern, the equal-distance mode focuses far more beams in the outer-swath areas and provides more consistent coverage and resolution across the entire swath opening. These types of systems can be particularly useful in bridge surveying applications for providing consistent coverage along the structural supports.

Proper installation of the multibeam sonar, as well as tight integration with the other peripheral sensors is critical to ensuring the accuracy of the multibeam survey results. Although the acquisition of multibeam data can proceed rapidly once the system has been properly installed and calibrated, the processing of the data can be a more time-consuming effort, particularly in areas of high vertical relief or significant water-column interference. As will be discussed later, editing multibeam data that has been acquired around bridges can be particularly challenging. After the various multibeam sensor data have been edited and verified, the sounding data are reduced to a vertical datum (e.g., MLLW, NAVD88, etc.) based on water-level correctors developed from accurate elevation data acquired on the survey boat or local observations. After the bathymetric data are fully edited and reduced to a datum, comparisons are then made on the areas of overlap that are generally seen in multibeam datasets. Eventually, the multibeam data are gridded based on desired resolution and file size constraints, and then exported to a GIS for additional analysis, visualization, and integration with other data types (Figure 1).

In addition to high-resolution bathymetry, most multibeam systems are capable of acquiring acoustic backscatter intensity data that provides useful information for helping to characterize seafloor sediments. Handled similarly to side-scan sonar data, multibeam backscatter data are typically merged to create imagery mosaics that are used to help delineate and distinguish areas of differing seafloor sediments (Figure 1). For target detection, the resolution and image quality of multibeam backscatter data may be somewhat lower than true side-scan sonar data, primarily because of steeper grazing angles; the multibeam transducer is typically mounted on or near the survey vessel, while the side-scan sonar transducer is housed in a towfish that is maintained closer to the seafloor. For general seafloor characterization, multibeam backscatter data offer some advantages over side-scan sonar data. The positional accuracy of the backscatter data is usually much better because of the fixed and well-known location of the transducer, as well as the accurate vessel heading and motion data that are also acquired. In addition, the backscatter intensity data can usually be normalized across the swath by accounting for sonar settings, beam angle geometry, and seafloor bathymetry. This produces datasets and mosaics that are more consistent and easier to analyze through either manual or automated methods.

OTHER ACOUSTIC SURVEY TECHNIQUES

Other acoustic remote sensing sensors that have also been used to support bridge-related surveying applications include single-beam echosounders, side-scan sonars, and sector-scanning imaging sonars. Even with the relatively recent advances in shallow-water multibeam technology, there are still applications well suited for single-beam bathymetry and it remains an accurate, low-cost, and relatively simple technique for generating seafloor topography. For many years, single-beam “fathometric” surveys have been a standard requirement within many underwater bridge inspection programs. In these applications, the single-beam data has been used to develop general bathymetry around the site of the bridge and to make an initial assessment on scour. However, based on the lane spacing used during data acquisition, single-beam bathymetric survey data will typically cover only 5-10% of the total seafloor area (Table 1). Subsequent analysis and gridding tools can still be used to generate a three-dimensional seafloor surface model with this relatively sparse data, though a large degree of interpolation between the discrete survey data points will be required. Though this interpolation might work well in flat or gently-sloping areas, in steep or irregular areas the interpolation will be much less reliable and the resulting surface will not accurately reflect the true bathymetry. In addition to the much sparser data coverage, the single-beam techniques also provide no capability for acquiring data along vertical surfaces such as underwater bridge supports.

Side-scan sonar imaging has been used extensively over the last 30 years to provide a relatively quick and complete acoustic image of the seafloor surface, as well as to reveal the size and location of distinct objects on the seafloor. Side-scan sonar data and the resulting imagery mosaics provide a plan-view map image of the bridge area that can be useful for imaging bridge structural supports and also identifying debris and other objects around the supports (Table 1). However, because it is basically a two-dimensional map product, the side-scan sonar data is not useful for quantitatively evaluating bathymetry or scour around the structures or assessing the vertical faces of the underwater bridge supports.

In recent years, sector-scanning sonars have become more commonly used as a bridge inspection tool primarily to generate high-resolution acoustic images of the faces of individual structural supports (Table 1). The sector-scanning sonars typically operate at higher frequencies than the other sensors discussed and are capable of providing high resolution acoustic images that are commonly used for real-time obstacle avoidance on remotely operated vehicles (ROVs), small item detection, diver guidance, and structural assessment. Unlike the other systems that have been discussed where data is typically acquired from a moving vessel, development of the high-resolution sector-scan images requires a separate stationary set-up for each of the images produced. For this reason, sector-scanning sonars are viewed more as a higher-resolution imaging tool as opposed to a broader-scale mapping tool. Though geo-referencing of data points and generation of point cloud datasets is possible with sector-scanning systems, it is a more complex operation, requiring additional hardware and software. For bridge-related applications, the primary focus for the use of sector-scanning sonars has been in acquiring high-resolution acoustic snapshots of the faces of underwater structural supports.

A general comparison between these different acoustic survey techniques shows that each of these methods offers some trade-offs between cost, complexity, and types of data products that are produced (Table 1). Of these acoustic survey techniques, multibeam echosounding has probably had the least direct use in bridge-related survey applications, primarily due to the relative newness of the technology, as well as the complexities and related costs associated with conducting a high-quality multibeam survey. Not only are there greater hardware requirements, but it is also more of a technical challenge to properly install, integrate, and operate the equipment. However, once the system is properly set-up, multibeam echosounding can be used to efficiently acquire dense, fully geo-referenced datasets for the areas around the bridge, including each of the underwater structural supports. The resulting datasets can be used to generate gridded high-resolution bathymetric surfaces in the areas around the bridge, as well as dense point-cloud datasets of the structural supports. The gridded bathymetric surface products are useful for evaluating the complete area around the bridge and making an assessment of scour patterns, while the point cloud products are useful for a more detailed evaluation around each of the structural supports.

MULTIBEAM SURVEY CHALLENGES AROUND BRIDGES

Even with a properly integrated multibeam survey vessel, there are some unique challenges presented when trying to complete a high-resolution multibeam survey around a bridge. Almost all high-resolution multibeam surveys rely on real-time kinematic (RTK) differential Global Positioning System (RTK DGPS) data for tracking precise vessel position and elevation during the survey. In most cases, the overhead bridge deck creates an intermittent obstruction to at least some part of the GPS constellation that usually results in a short-term degradation in the GPS position and elevation quality. The impacts of the short-term degradation in GPS quality can vary greatly depending on a number of factors (e.g., number of available satellites, size and height of bridge, survey line orientation, etc.). Around bridges where the overhead obstruction might be particularly extensive, there are other positioning techniques (e.g., acoustic Doppler Velocity Log (DVL) bottom tracking, laser range/azimuth tracking, etc.) that can be used to augment the primary RTK DGPS.

Some of the GPS quality impacts can be controlled by planning the survey during a time period when there is a favorable GPS constellation and also aligning the survey lines to minimize potential obstruction impacts from the bridge. Usually a series of lines are run both perpendicular and parallel to the main bridge alignment. When running perpendicular to the bridge there will generally be high-quality GPS data at the start and end of the line, with a short-term drop in quality as the boat passes under the bridge. When running parallel to the bridge, it is important to have a sufficient GPS constellation visible on that side of the bridge to ensure adequate GPS quality. Many of these GPS quality concerns can be minimized by relying on the more robust GLONASS-enabled GPS receivers that are able to utilize the GLONASS constellation, effectively doubling the number of potential satellites available at any time.

During post-processing, it is usually possible to interpolate over a short-term degradation in GPS quality, particularly if higher-quality GPS data brackets the brief lower-quality period. This is often the case in survey lines that pass directly underneath the bridge. Often, a short-term loss of the most accurate “Fixed Narrow Lane” GPS solution will only have a noticeable impact on the computed elevation data that are primarily used to provide the necessary vertical reference (i.e., tide or water-level data) for the survey. In addition, though a 30cm drift may not be readily noticeable in the position data, it will be more apparent in the elevation data due to the vertical offset in the sounding results. Because the elevation data values tend to change relatively slowly, it is usually a straightforward process to correct for drift in the elevation data due to short-term GPS issues. There are also some more advanced GPS processing tools that allow for both a forward and backward re-processing of the raw GPS data that can provide a more accurate and robust position and elevation solution. These techniques enable the entire acoustic survey to be re-generated using the improved position and elevation data.

The other primary challenge associated with multibeam surveys around bridges revolves around the level of data cleaning often required for the data that is acquired around the underwater structural supports. A multibeam echosounder typically does “bottom detection” based on either amplitude or phase measurements from each beam. Over the seafloor, the mutlibeam acoustic return signals are relatively similar and the sonar can be tuned through gain and power settings to optimize the performance of the bottom detection algorithms. However, when the acoustic signal encounters the hard vertical face of a structural support most multibeam systems have a more difficult time resolving the bottom detection process. Though multibeam systems are generally able to properly track the bottom as they approach and run along a structure, they often have difficulties re-acquiring the true bottom as they maneuver away from the structure.

The difficulties associated with bottom detection around the vertical bridge structures, usually results in a noisy acoustic dataset around these areas. Though some of these problems can be minimized by careful attention to sonar tuning during data acquisition, it is inevitable that careful manual cleaning will be required in the areas around most of the underwater supports. Because these challenging areas will have been covered by multiple survey lines along multiple orientations, it is important that the individual lines be edited carefully prior to examination within an area-based editor. Because the position tolerances are very tight in the areas around the vertical surfaces, if potential position issues cannot be resolved for a specific line, then that line should be excluded from the subsequent editing process. In the end, careful manual cleaning within an area–based editor will be required to create datasets that accurately reflect the vertical structure.

MULTIBEAM SURVEYS FOR UNDERWATER BRIDGE INSPECTIONS

The Federal Highway Administration’s (FHA) bridge inspection requirements specify that all bridges with any underwater supports must be inspected at no greater than a five year interval. Most existing bridge inspection techniques are focused on structural assessment and rely primarily on diver visual or sometimes sector-scanning sonar techniques. Many of these same inspection programs have also included some type of initial single-beam fathometric survey requirement, though the re-survey requirements seem to vary a great deal by state. Due to certain environmental conditions (e.g., deep water, strong currents, and murky water), underwater inspections of some bridges can be difficult and sometimes dangerous. In addition, the existing structural assessment methods, like visual inspection or sector-scanning sonar, are not well-suited for making an accurate or complete quantitative assessment of scour around all of the structural supports. Over the years, scour around the structural supports has proven to be the primary cause for most major bridge failures. Though it will not replace the need for periodic “hands-on” structural evaluations through either diver visual methods or scanning sonar techniques, the multibeam survey approach offers a number of unique benefits as a bridge assessment tool. The following section provides an overview of the methods and results for a recent bridge inspection multibeam survey project.

Representative Multibeam Bridge Inspection Project

The Maine Department of Transportation (ME DOT) has one of the more robust underwater bridge inspection programs in the nation, as part of its effort to ensure the structural integrity of the state’s bridges and comply with the FHA’s bridge inspection requirements. ME DOT currently has a 12-person professional dive team that conducts bridge inspections at intervals of no greater than five-years for each of the state’s bridges that rely on underwater structural support. Due to strong currents and restricted visibility, underwater visual inspections of certain bridges - including three that span the Kennebec River in the towns of Bath and Richmond, Maine - can be particularly difficult for divers to manage. In light of these challenges and the safety risks posed for its divers, the ME DOT recently chose to use multibeam bathymetry to meet their underwater bridge inspection requirements.

Substructure, Inc. of Portsmouth, NH was selected by ME DOT to conduct high-resolution multibeam surveys of the Bath and Richmond bridges, utilizing the company’s survey vessel *Orion*. Though these bridges had been in place for many years, what was deemed to be the initial “baseline” surveys of the Bath and Richmond bridges were conducted by Substructure in June 2009 during an unusually high flow period on the Kennebec River. In July 2010, Substructure conducted an additional baseline survey of the Sheepscot River Railroad Bridge, and also returned to the Richmond Bridge to conduct a follow-up “current-conditions” survey (Figure 2). This re-survey of the Richmond Bridge was completed to obtain comparative multibeam survey and scour data that could be used for computing a depth difference surface between the two surveys and evaluating the erosional and depositional patterns around the bridge.

Prior to the start of each multibeam survey operation, Substructure established a real-time kinematic (RTK) differential Global Positioning System (DGPS) base station over a known survey control point provided by ME DOT to ensure high resolution vertical and horizontal accuracies (cm-level) throughout the survey operations (Figure 3). This level of accuracy was critical to ensure proper positioning and imaging of the structural supports for each of the bridges and also the consistency of the data between different survey periods. Substructure's custom built survey vessel *Orion* was used to acquire extensive multibeam data around each of the bridges (Figure 3). Standard survey equipment on *Orion* includes an R2Sonic 2024 multibeam echosounder, Applanix 320 POSMV vessel motion reference and navigation unit, Odom Digibar speed of sound profiler, and HYPACK/HYSWEEP hydrographic data acquisition and processing software. For these surveys, the multibeam transducer was rotated outward 20° so multibeam data could be acquired almost up to the water surface on the port side, maximizing data coverage around the structural supports.

Final data deliverables for both baseline and current-conditions surveys include gridded products that were created by averaging or selecting just the shallowest sounding within a half-foot square grid across the entire survey area. The tightly gridded dataset provides a high-resolution view of the entire survey area around the bridge, while helping to reduce the overall size of the dataset. The gridded datasets are used to create various hillshade surface models around the bridge that can be manipulated in a variety of ways to help with the visualization of the overall bathymetry around the bridge (Figures 4 & 5). These gridded datasets are also used to compute the depth difference surfaces between surveys that are used to evaluate local seafloor change. Within a smaller area around each of the structural supports, numerous full-resolution point cloud datasets were created that included all of the valid multibeam soundings within that area. These dense datasets were manipulated within a cloud data viewer to produce numerous static images of each of the supports. Several of these images were eventually included within the final bridge inspection report (Figure 6 & 7).

In addition, a comparative depth difference grid surface was also created between the initial baseline survey and the subsequent current condition survey around the Richmond Bridge (Figure 8). This depth difference grid quantitatively depicted the relative change across the entire area between the times of the two surveys. Even subtle areas of change, such as migrating sand waves, could clearly be seen in the depth difference results. In addition, larger areas of more uniform change could also be detected and examined. This enabled a more complete assessment of the erosional and depositional patterns across the entire bridge area. This in turn, allowed a more comprehensive evaluation of the scour potential around the structure, both in the near term and in the future.

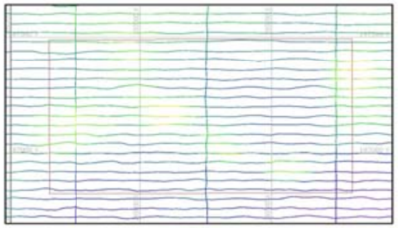
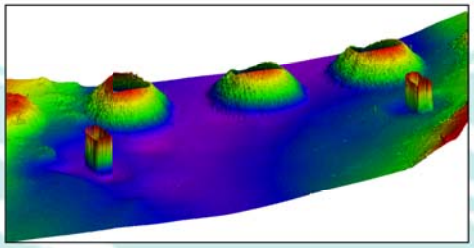
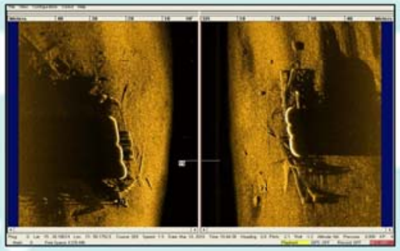
CONCLUSION

The US Army Corps of Engineers (USACE) New England District has recently begun to require pre- and post-construction multibeam surveys for all new bridge construction that may have the potential to impact a federal navigation channel. This is a permitting and regulatory requirement that is primarily focused on ensuring that the bridge construction project does not create any obstructions or other hazards to navigation within the navigation channel. Though the intent of these pre- and post-construction multibeam surveys is focused primarily on evaluating impacts to navigation, they also have the potential to provide high-resolution baseline survey data around the new bridges that should prove useful for future inspection and monitoring operations. If similar programs were in place in other regions of the country, then perhaps that could help to provide the impetus to begin to utilize the richness of multibeam survey data to help conduct a more thorough and comprehensive bridge inspection program.

Multibeam acoustic surveys are not intended to replace the need for periodic “hands-on” bridge structural evaluations through either diver visual methods or scanning sonar techniques. And as mentioned previously, only a relatively small subset of the bridges with underwater structural supports occur in environments where the multibeam methods would be viewed as an applicable survey technique. However, in areas with certain environmental characteristics (e.g., deeper water, complex bottom topography, limited visibility, strong currents, etc.) multibeam surveying offers a number of unique benefits relative to any other existing assessment techniques.

- Efficient and accurate assessment of the bridge structure, as well as the entire area encompassing the “bridge system”;
- Rich and robust datasets that can be used for both quantitative and qualitative data analysis, visualization, and image creation;
- Conducting repeat surveys with consistent datums provide system-wide comparative data to quantitatively assess scour and movement of material over time;
- Safe and efficient acquisition of high-resolution survey data under a wide range of environmental conditions;
- Ability to identify areas of structural concern that might warrant follow-up diver investigation.

Tables and Figures

Technique	Data Type & Coverage	Resolution	Primary Data Products / Relevant Info	Sample Data Products
Single-Beam Echosounder	Bathymetry Along-track point data	Vert - cm Horiz: cm - m	Sparse, low-resolution bathymetry Relatively low cost and complexity "Fathometric surveys" in bridge applications Common Frequencies: 20 - 400kHz	
Multibeam Echosounder	Bathymetry Imagery Wide Swath Point Data	Vert - cm Horiz: cm - m	High-resolution bathymetry and backscatter imagery High cost and complexity Effective at mapping vertical structures Proper installation and integration are critical Common Frequencies: 200 - 450kHz	
Side-Scan Sonar	Imagery Wide Swath Point Data	Vert - N/A Horiz: m	Geo-referenced 2D plan-view mosaic Moderate cost and complexity Towfish positioning drives horizontal resolution Characterize sediments / identify objects Common Frequencies: 100 - 1200kHz	(a) 
Sector-Scanning Sonar	Imagery Image From Occupied Point	Vert - N/A Horiz: cm - m	Non-georeferenced 2D image of structural face Moderate cost and complexity Geo-referencing and point cloud creation is complex Quanatitative bathymetry data is limited Common Frequencies: 300 - 1200kHz	(b) 

(a) Image courtesy of Edgetech (www.edgetech.com/edgetech)

(b) Image courtesy of Kongsberg (www.kongsberg-mesotech.com/)

Table 1. *Overview of acoustic survey techniques that are used to support bridge-related survey activities.*

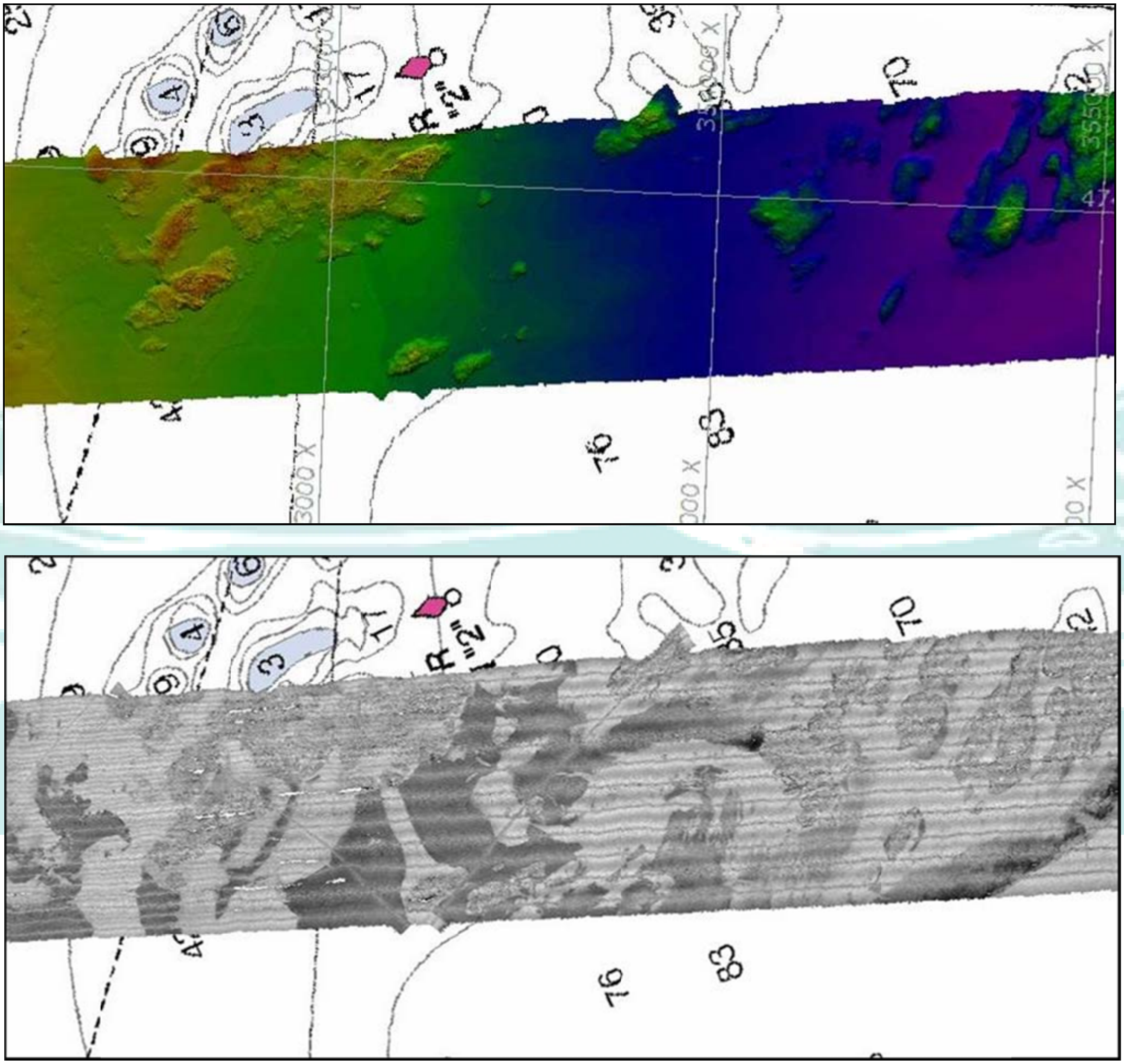


Figure 1. *A hillshade bathymetric surface model (top panel) and a backscatter imagery mosaic (bottom panel) created from the same multibeam dataset that was acquired by Substructure's Orion in July 2010 along a rocky reef area off the northeast coast of Massachusetts. This dataset was acquired in support of a research project conducted by the University of New Hampshire's Center for Coastal and Ocean Mapping (UNH CCOM).*

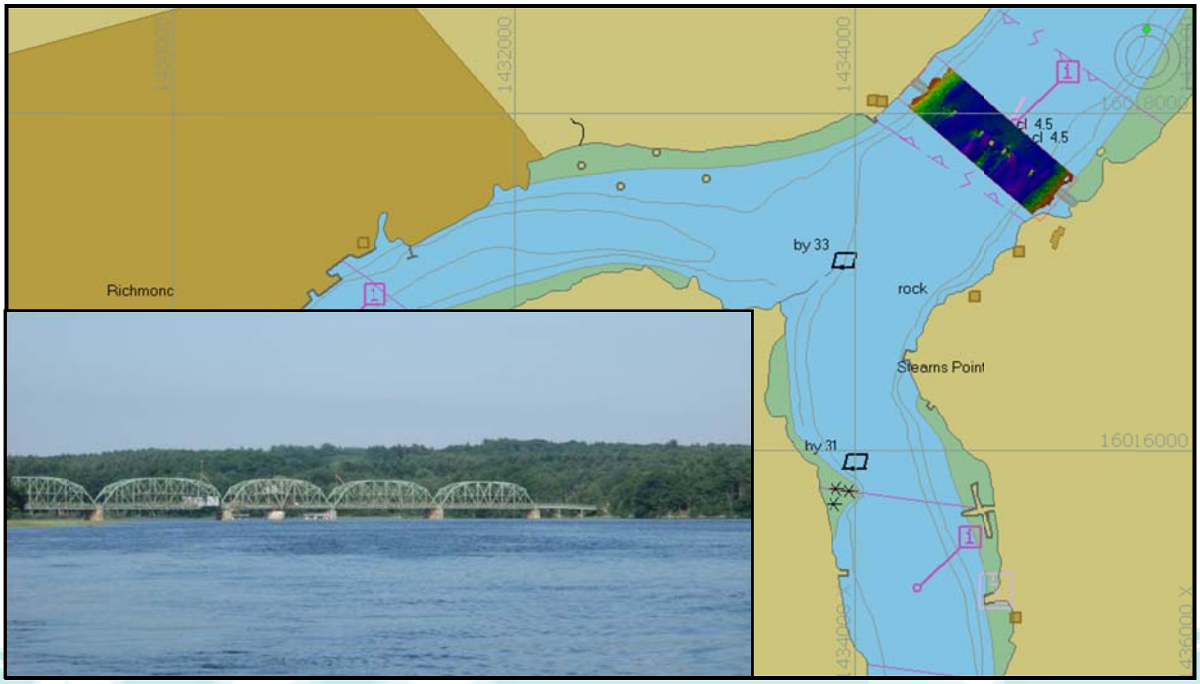


Figure 2. *The location of the recent survey of the Richmond Bridge is shown on NOAA Nautical Chart US5ME18M. The inset photo is an image of the Bridge looking upriver from the town of Richmond.*

Figure 3. *In the left photo, Orion is maneuvering near the eastern side of the Richmond Bridge during survey operations in July 2010. The RTK DGPS base station can be seen in the foreground set-up on a survey monument that was established by ME DOT. In the right hand photo, Orion is maneuvering close to the center turnstile support during survey operations.*

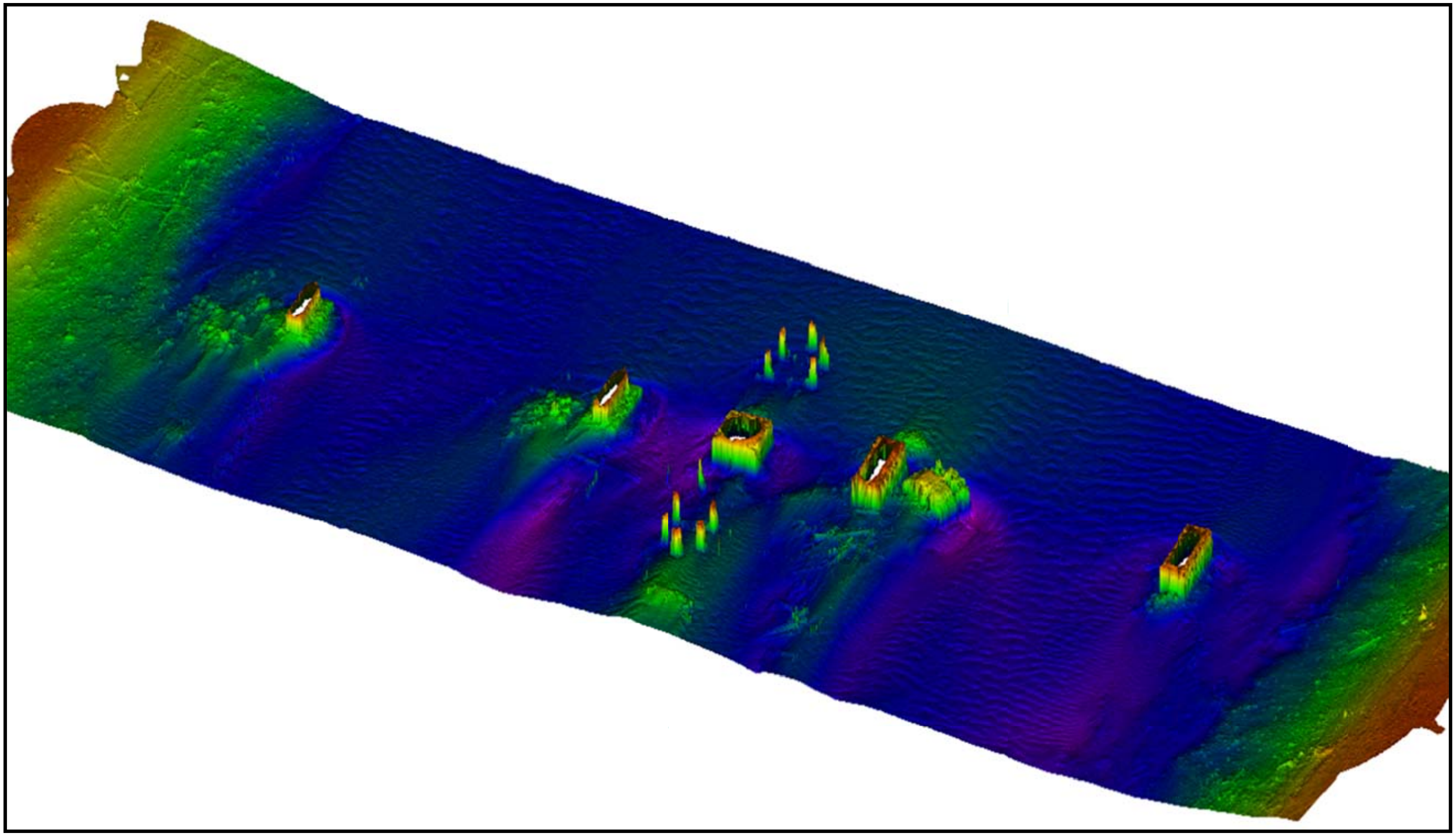


Figure 4. *Rotated color hillshade bathymetric surface model of an area around a highway bridge over the Kennebec River near Richmond, ME. The hillshade surface model was generated from a 0.5-foot minimum grid created from R2Sonic 2024 multibeam data acquired on Orion. The bridge has five main supports over the river, with a round turnstile on the center support. Five-pile ice deflector structures are also located upstream and downstream of the center support. Extensive debris and one large obstruction were also evident in the vicinity of the supports.*

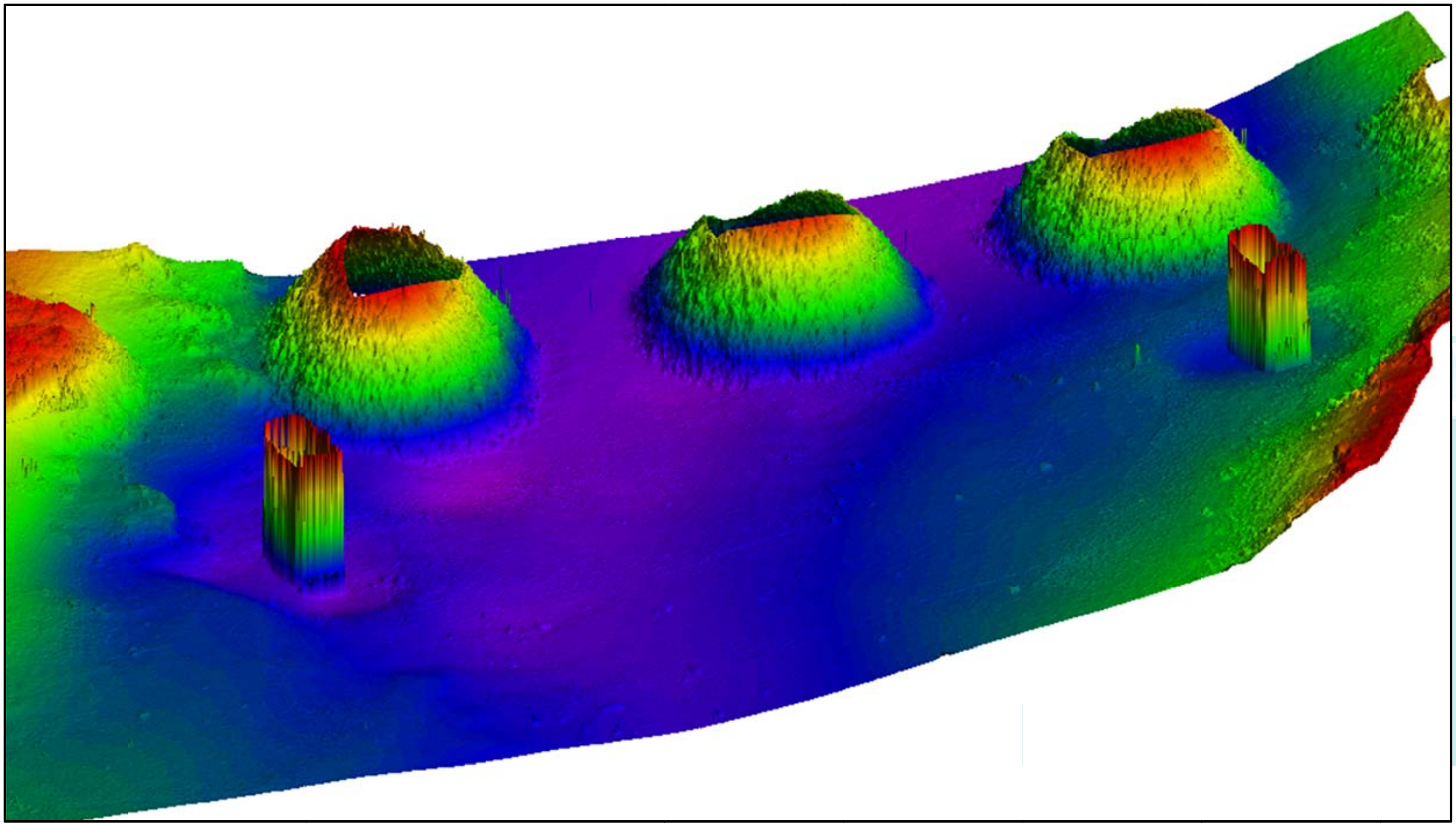


Figure 5*. Rotated color hillshade bathymetric surface model of an area around a railroad bridge over the Sheepscot River near Wiscasset, ME. This hillshade surface model was developed from a 0.5-foot minimum grid created from R2Sonic 2024 multibeam data acquired on Orion. The structural supports from the existing bridge are in the foreground, while the prominent rubble mounds remaining from a previous bridge are in the background. Though these rubble mounds posed a significant hazard to navigation that became visible during low tide, they were not represented on the applicable nautical charts for this area.*

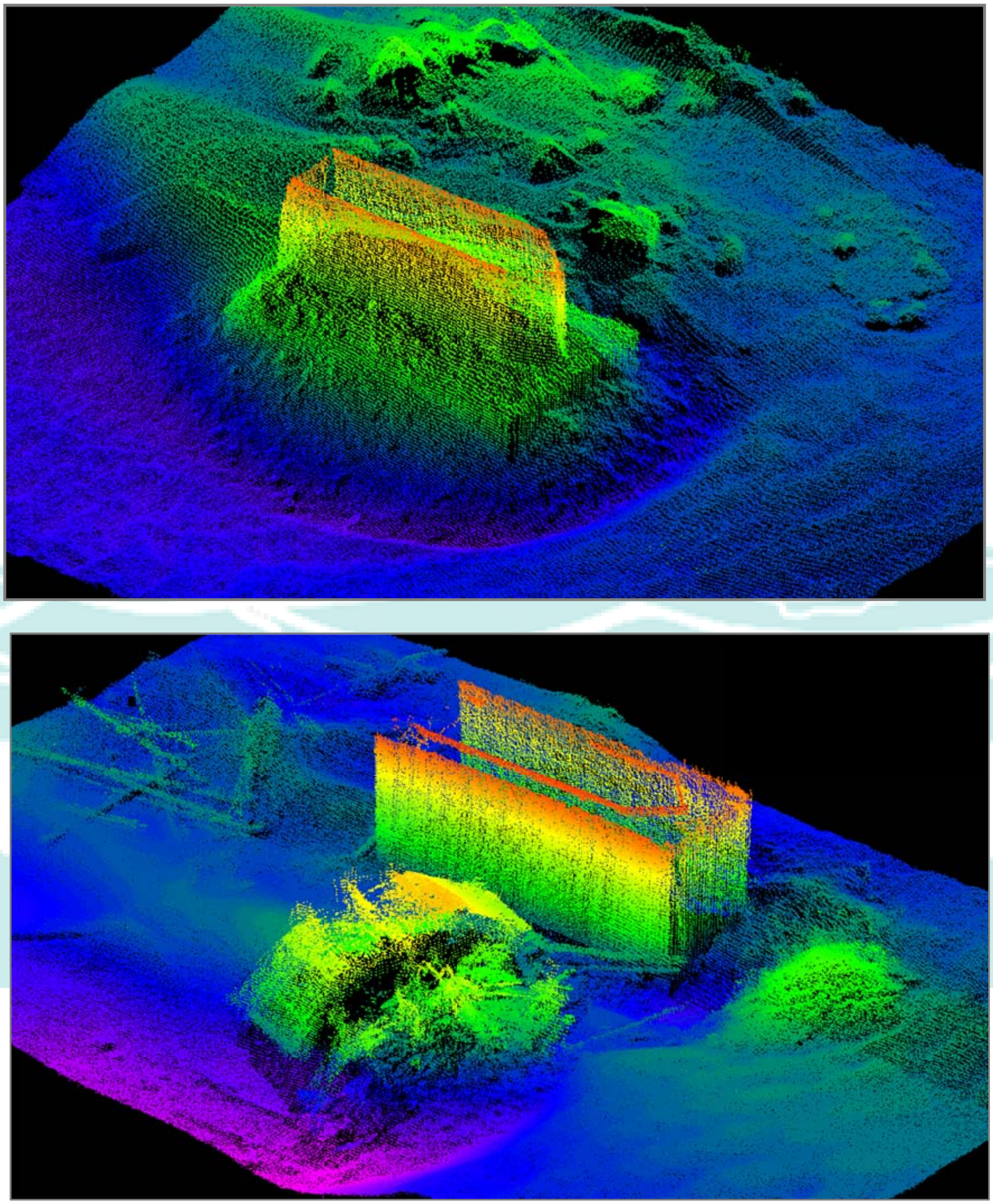


Figure 6. *Top Panel - Point cloud image of one of the structural supports for the bridge over the Kennebec River near Richmond, ME. The point cloud image includes all of the valid multibeam soundings and provides a higher resolution view of a particular area. Relatively significant scour can be seen along the leading edge of the footing for this support. Bottom Panel - Point cloud image of another structural support showing a prominent obstruction adjacent to the support. In addition to the large obstruction, extensive debris (e.g., logs, rubble, etc.) is also evident around this support. In this case, the more significant scour is occurring around the outside of the obstruction.*

Figure 7. *The top photo shows the center support for the Sheepscot River Railroad Bridge while the photo at left shows a close-up view looking upriver at the support. The two point cloud data images include an overhead view and a rotated view looking downstream. Some Initial concerns about the wavy appearance of the point cloud images were resolved at low tide when the deteriorating remnants of the original sheet pile form could be seen at the water line. The point cloud results reflected the sheet pile form and not the main stone supports.*

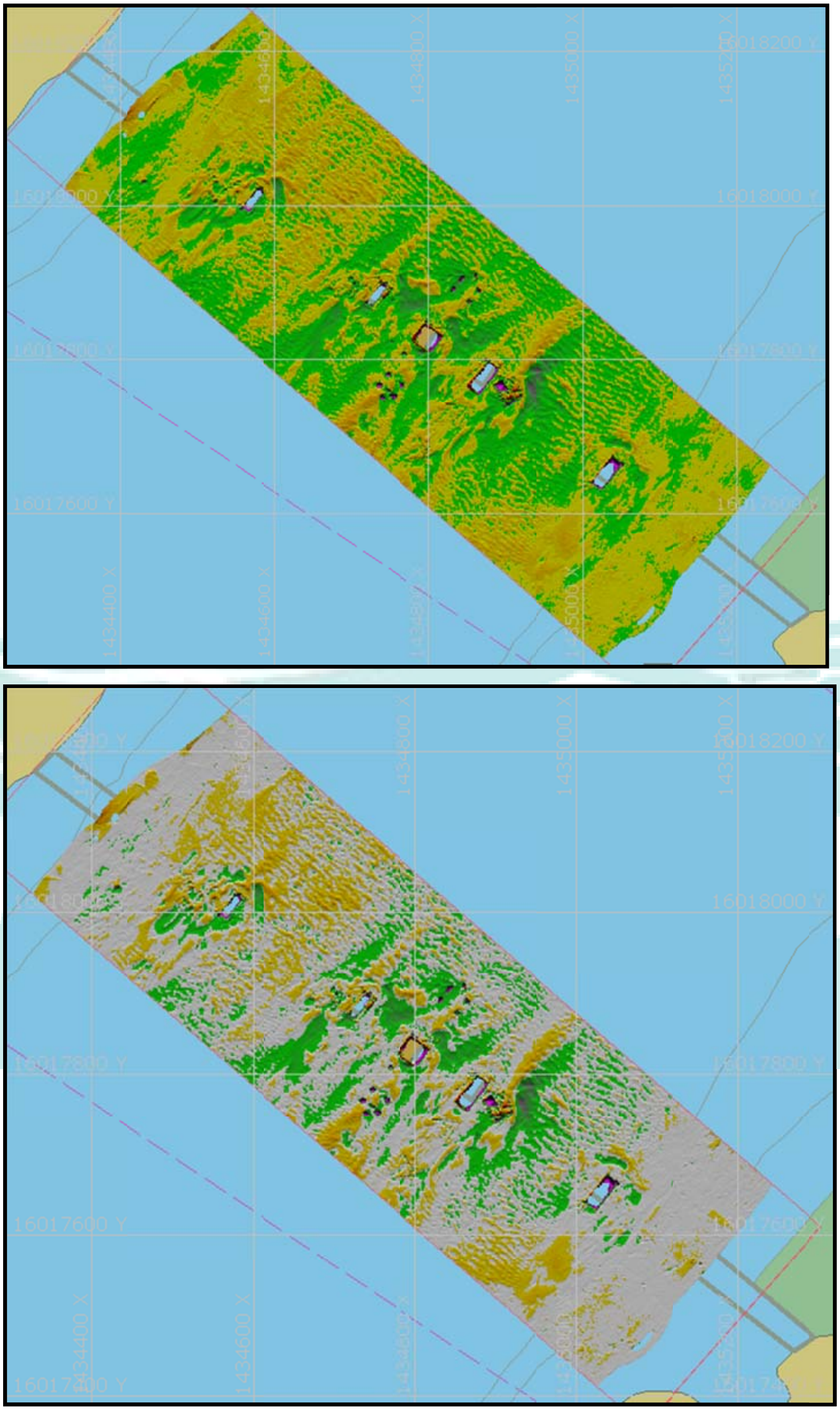


Figure 8. *Color hillshade surface model of the area around the Richmond Bridge, based on a one-foot depth difference grid that was created between the June 2009 multibeam survey and the July 2010 multibeam survey. In these figures, the green colors indicate erosional areas (or areas that were deeper in 2010) and the yellow colors indicate depositional areas. To help highlight the areas where greater change has occurred, the bottom panel shows the same grid, except that the areas that differed by less than 0.25 ft (plus or minus) have been shaded white.*