UNDERWATER INSPECTION OF HIGHWAY BRIDGES – RECENT TRENDS AND TECHNOLOGIES

BY DAVE SEVERNS, P.E.

Underwater engineering evaluations of transportation assets have historically relied largely upon conventional, crewed commercial diving operations, using visual testing (VT) and tactile examination methods to detect surface discontinuities and evaluate site conditions. In practical application, this approach alone is often found to be suboptimal, due to multiple challenges inherent in conducting inspections in the underwater environment. Modern underwater inspections are increasingly reliant upon new technologies, and nondestructive testing methods beyond VT are used during conventional diving inspection to gain a broader picture of the asset and its condition, increasing efficiency while lowering risk in the process. Underwater engineering inspectors today employ traditional nondestructive technologies, including VT, ultrasonic testing (UT), and magnetic particle testing (MT) techniques, in concert with acoustic (sonar) imaging techniques and remotely operated vehicles (ROVs) to obtain more detailed information about the asset and adjacent waterway conditions. This approach enhances the inspection's safety and efficiency and reduces risk to the bridge owner and end user. This article discusses today's underwater bridge inspection approach, emphasizing the NDT technologies utilized and their benefits.

Introduction

As transportation assets within the United States continue to age, the need to manage their performance and ensure their safety becomes increasingly important. This is especially true for the nation's bridges, which rely on periodic safety inspections to assess condition and determine needs for maintenance, repair, and eventual replacement. Bridge safety inspections are mandated by federal regulation, falling under the jurisdiction of various federal agencies including Federal Highway Administration (FHWA), US Department of Defense, Bureau of Reclamation, Bureau of Indian Affairs, US Forest Service, and others. According to 2021 National Bridge Inventory (NBI) data, there are approximately 500 000 bridges in the United States that span waterways. Of those, nearly 30 000 bridges exhibit submerged substructure elements that require stand-alone underwater bridge inspection. This article will discuss the historical state of practice regarding conducting regularly scheduled National Bridge Inspection Standards (NBIS) underwater bridge inspections, including their use of NDT techniques, as well as a newer, more innovative approach marrying conventional, commercial diving techniques with more advanced non-destructive technologies, including sonar imaging and remotely operated vehicles (ROVs). Some example procedures employed in this enhanced work approach will be presented, along with their advantages.

Historical Inspection Approach

Underwater engineering evaluations of bridge assets have historically involved conventional, commercial diving operations, using visual testing (VT) and tactile examination methods to detect surface discontinuities and evaluate site conditions. Underwater inspections are required on a maximum 60-month inspection interval for all highway bridges in the United States, as per 23CFR650 National Bridge Inspection Standards (NBIS), with oversight provided principally by the FHWA as well as individual bridge owner-agencies. Aided by high-intensity underwater lamps and small hand tools to facilitate cleaning and rudimentary measurement, the formally accepted inspection practice is for the inspection team to conduct a "Level I" "swim by" cursory inspection of the asset, in conjunction with a "Level II" hands-on, tactile examination of the asset elements, involving the localized removal of biofouling to expose the element surface. Unless otherwise scoped, the use of specialized testing to evaluate material properties or identify subsurface conditions has typically been conducted on an as-needed basis, as a "Level III" detailed, or "in-depth" inspection.

The water body spanned by the bridge is also typically evaluated during the underwater inspection, to evaluate both geomorphologic aspects (the shape and physical characteristics of the waterway) as well as to detect scour (erosion of the banks and underwater channel bed caused by flowing water). Waterway inspection procedures during a typical NBIS underwater bridge inspection rely on VT, in conjunction with a conventional echo-sounding fathometer, to chart channel bottom profiles both along the exterior edges of the bridge as well as adjacent to individual substructure units. Channel bottom depth data is post-processed and converted into elevations, which, in turn, can be compared to past data as well as analytical data identifying critical bridge foundation elevations raising structural concerns.

Trusted NDT Technologies

Since the 1960s, transportation assets have been evaluated by divers using a combination of NDT devices that migrated inland largely from the offshore oil and gas fields, combined with modified "topside" (above water) NDT testing equipment and a few improvised pieces of gear. In addition to VT using ubiquitous handheld or helmet-mounted high-definition photographic and video cameras, measuring devices (usually wooden folding rulers) and clear water boxes (used to aid still photography in murky waters), inland diver inspectors conduct underwater structural inspections using a small variety of hand-held NDT devices.

Ultrasonic Testing (UT)

Other than VT, select UT methods are by far the most common NDT technology employed during underwater bridge inspections to identify, locate, and size discontinuities in steel, timber, and concrete members. The equipment used underwater comes in two varieties: modified topside ultrasonic equipment, typically consisting of a transducer connected with a long cable to a conventional topside UT scope; or a self-contained, water-tight unit handheld by the diver (see Figure 1). In the former instance, the diver manipulates a straight-beam or angle-beam transducer underwater while readings are taken from a topside technician who controls the UT instrument in a clear, benign environment. More common today is self-contained equipment built specifically for use underwater (see Figure 2).

Figure 1. Underwater-capable UTT unit with long transducer cable.

Figure 2. Diver held UTT unit. Note display visible to diver.

Ultrasonic thickness testing (UTT) is the most common UT technique employed during underwater bridge inspections. It is commonly used to obtain thickness measurements in steel members. The member to be tested is cleaned to establish a clean, smooth surface, and measurements are obtained in predetermined locations. For substructure supports using steel piles or columns, section measurements are typically obtained in the splash zone, at the mudline, and near the midpoint of the water column. The results are typically archived in a matrix format, for ease of comparison to future measurements taken in the same areas. From this, deterioration rates may be established. Section thickness data of concern is evaluated analytically and appropriate actions are taken, which might include corrosion mitigation measures, structural repairs, or, in extreme instances, modifications to loading of the element(s) until repair or replacement actions are effected. UTT equipment used in the field is almost exclusively of the self-contained variety.

Ultrasonic angle-beam testing using shear waves (such as shear wave and phased array ultrasonic testing) is conducted on a very limited scale (primarily during in-depth, Level III inspections) on submerged bridge members for the inspection of welds, crack detection, and for sizing of discontinuities. While both single-element and multi-element phased array systems have been adapted for use underwater, the latter equipment type is seldom used during underwater bridge inspections. Unlike UTT, angle-beam testing in the inland environment is usually conducted using a topside scope, and the diver is merely manipulating the transducer, due to limitations introduced by water turbidity.

Magnetic Particle Testing (MT)

MT plays a diminished role in underwater bridge inspection as compared to its use in the offshore underwater inspection industry. Diver-manipulated yoke systems are at times used, but principally only during Level III inspections in clear, calm waters, where the powdered metallic filings can be applied and indications can be seen by the diver (see Figure 3). Unfortunately, these conditions are not often experienced in the inland environment.

Figure 3. Underwater MT system, with diver-held yoke and lamp.

Other NDT Methods

Other NDT methods and techniques are available to the underwater bridge inspection team for testing of steel members. Techniques such as acoustic emission testing (AE), time of flight diffraction (TOFD), and underwater pulsed eddy current (PEC), while in use in the offshore inspection arena, have not readily advanced into the inland bridge inspection industry. Underwater PEC in particular holds promise, considering that the technology is specifically designed to detect corrosion hidden under marine growth or coatings. Steel wall thickness can thus be measured without time-consuming surface preparation in piles, caissons, and the like.

With respect to the underwater inspection of concrete, several commercially available testing instruments have successfully been modified and tested for underwater use. Conventional rebar locators, operating to detect a magnetic flux disturbance caused by an embedded ferrous object, may be used underwater to locate and size rebar, as well as to measure the amount of concrete cover. Rebound devices (also known as the "Schmidt hammer") that evaluate the compressive strength of concrete have also been successfully modified to operate underwater. UT methods are also available to estimate compressive strength and detect hidden discontinuities in concrete members. While easily operated by the diver, working in concert with trained above water testing technicians, each of these technologies has to date seen limited use in the underwater inspection of in-service bridge assets.

A More Innovative Approach

The historical VT-biased, "hands-on" approach to conducting underwater bridge inspection described above has been developed to detect discontinuities and evaluate conditions with relative celerity and reasonable levels of inspection quality. In practical application, however, this approach is often found to be suboptimal, due to the multiple challenges inherent in conducting inspections in the underwater environment. As with inspection work conducted in dry environments, underwater VT examines only the exterior surface of the asset's elements. Additionally, while diver-operated NDT test methods are helpful, the risk factors lying within the underwater environment—minimal visibility, extreme cold, submerged drift and debris, stubborn biofouling, chemical and biological pollution, vessel traffic, dangerous aquatic animals, inspection time limitations imposed upon the dive team by physiologic restrictions to diving at depth, coupled with a nationwide lack of divers themselves—introduce physical barriers and psychological restrictions precluding a thorough inspection of the asset. This being the case, the NBIS in 23CFR650.305 ("Definitions") defines an underwater inspection as one involving wading, diving, or "other appropriate techniques."

Consequently, modern underwater bridge inspections are increasingly reliant upon marrying new technologies and NDT methods with conventional, crewed diving inspection to gain a broader overall picture of the asset and its condition, increasing efficiency while lowering risk in the process. Underwater engineering inspectors today utilize traditional VT and handheld UT and MT techniques, in concert with acoustic imaging techniques as well as NDT-capable ROVs, to obtain more detailed information about the asset's elements as well as the bridge site at a more macroscopic level.

Acoustic Imaging (Sonar) Inspection

Sonar technology plays an ever-increasing role in today's underwater bridge inspection procedures, both to increase inspector safety and improve inspection quality. Sidescan, sector-scan, multibeam, and real-time volumetric imaging sonar systems each play a role, and all have the ability to "see" underwater when little or no visibility exists to the human eye. While a sonar unit cannot remove marine growth, reliably detect hairline cracks, or thoroughly measure the penetration depth of foundation undermining at a bridge pier, it can outperform a diver in many other areas, including the measurement of local scour holes (in clear water conditions), in assessing opening widths and heights of scour voids under bridge foundation elements, in visualizing debris accumulations and other hazards adjacent to a bridge pier, and in the ability to assess the sizeable areas of streambed situated out and away from the pier face. Considering that the number-one cause of bridge failure worldwide is scour (and not those superficial, hairline cracks), and considering that most bridges span waterways exhibiting adverse conditions (deep, turbid, debris-laden, and/or swift water), one can make a strong case for mandating sonar assessments in certain inspection scenarios.

To assist in the assessment of sonar technology during underwater bridge inspections, on 14 June 2018, the FHWA released Technical Report FHWA-HIF-18-049, *Underwater Inspection of Bridge Substructures Using Imaging Technology*, which evaluated various sonar imaging technologies and compared their performance in real-world bridge inspection tests to conventional data collection using divers. As per the report's abstract, the study determined that:

- Sonar technology is capable of identifying larger-scale characteristics of interest such as scour holes, debris, and moderate to large size voids and protrusions. It is more limited in identifying small-scale cracks or features hidden by marine growth.
- Sonar is particularly effective in adverse conditions where limitations on diver bottom time exist, such as deep water, and conditions where diver safety or mobility is of particular concern including swift currents or turbid water. In all environments, including those with adverse conditions, sonar technology is useful for identifying macro features quickly.
- Sonar technologies can be used to inspect underwater structural elements where divers cannot work effectively, to guide divers for a closer look, or to provide independent inspection insights. Sonar can also be effective in covering large areas quickly.

The study reported two overall conclusions:

- "Sonar inspections have not demonstrated the ability to identify some smaller scale elements of substructure condition that may be important in assessing the bridge and recommending maintenance."
- "Sonar technologies offer significant opportunities for improving underwater bridge inspections, especially in adverse environments or to inspect extensive areas."

In summary, the study found that sonar cannot replace diver inspectors, but can yield an improved process when conducted in combination with traditional diving inspection.

Depending upon the technology of choice, sonar equipment uses a remotely controlled sonar head that is either hard-mounted, pole-mounted in a boat, towed, or even affixed to an autonomous watercraft. The newest technologies even provide "live" data capture, offering a 3D display in real time. Each sonar technology has its own advantages, as highlighted in the following.

COURTESY: BRIAN ABBOTT

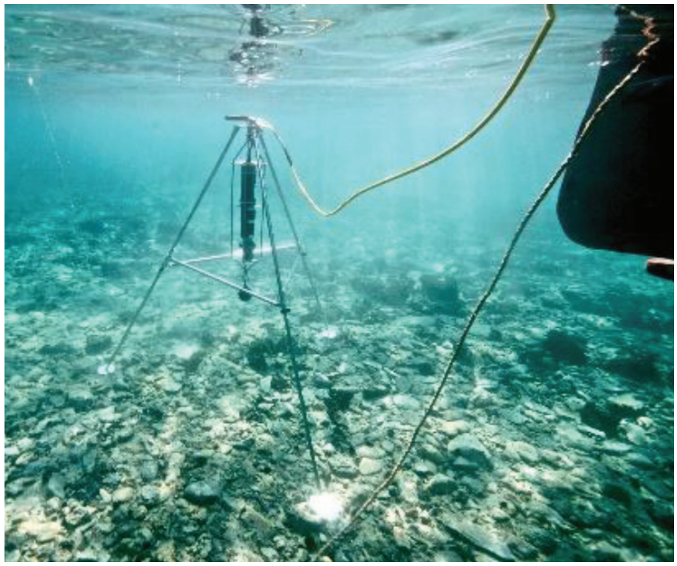


Figure 5. Sector scan sonar head deployed in a tripod on channel bottom.

Sidescan Sonar

A tried-and-true technology with offshore origins, sidescan sonar employs a towed or otherwise transported "fish" that continually moves through the water while scanning the channel bottom off to both of its sides. This technology yields processed data images with excellent resolution, readily revealing areas of local scour, pier foundation exposure, and accumulated drift and debris better than a diver can envision. One recent and unique adaptation of sidescan has been its integration into small autonomous watercraft, which can be deployed to gather bridge scour data adjacent to bridge piers during flooding conditions, before divers can safely access the bridge site (see Figure 4). Such systems are currently in use with several state DOT agencies and other service providers to help engineers make public safety decisions during emergency situations. (As an example, Figure 13 displays a typical data output screen from an autonomous vehicle system using sidescan sonar.)

Sector-Scan Sonar

Another established and valuable technology, sector scan employs a rotating head containing one or more sonar transducers, which is rotated in staccato fashion via a stepper motor, to gather image data of up to 360° from a single static deployment. Mounting of the scanning sonar head is quite flexible, as it may be rigidly mounted, attached to a pole for boat use, or deployed hanging vertically from a tripod which is lowered to the channel bottom. Tripod deployment of a sector-scan sonar head is illustrated in Figure 5. Individual scans can typically be completed in a few seconds, and output data of the site is displayed in either

COURTESY: HYDRONALIX

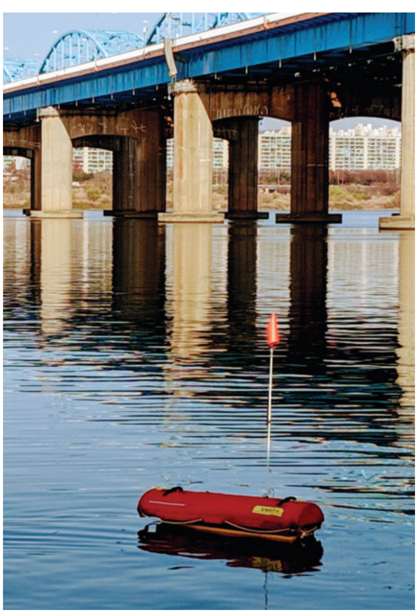


Figure 4. Autonomous vessel equipped with sidescan sonar evaluates a bridge.

COURTESY: BRIAN ABBOTT

Figure 6. Post-processed sector scan image, showing elevation view of pier.

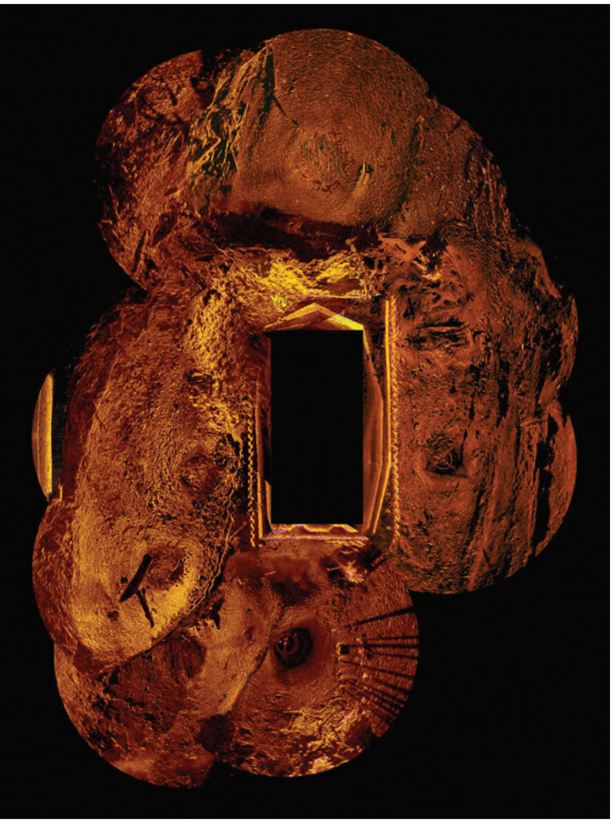


Figure 7. Plan view mosaic of channel bottom surrounding bridge pier using sector scan.

plan or elevation view. Figure 6 illustrates an elevation view output image. Multiple plan view images can be post-processed as mosaics to cover large areas of concern (see Figure 7), while elevation scans of individual bridge piers can be post-processed to show image views combining above- and below-water portions of a bridge pier as though they were a single photograph (see Figures 6 and 11 for reference). Scanning sonar software allows image data to be interrogated in real time, so as to calculate distances and dimensions of elements or defects and display them directly on the output images without the need for additional post-processing.

Sector scanning sonar has been used during underwater bridge inspections for many years and plays a fundamental role in the industry today, for both diver safety and inspection data acquisition. For example, prior to deploying an inspection diver, multiple plan view scans can be taken around the perimeter of a pier to quickly establish "safe zones" for subsequent diver deployment in areas free of drift and debris. Additionally, the angular range of the scan can be narrowed to focus in on a specific "swath" or area of concern. Thus, the sonar can be operated once the diver has entered the water to track them in real time as they conduct the inspection. Several state DOT agencies require acoustic imaging of bridge substructure elements as a part of their underwater bridge inspection procedure, and post-processed sector scan images are a common deliverable for those owners.

Multibeam Sonar

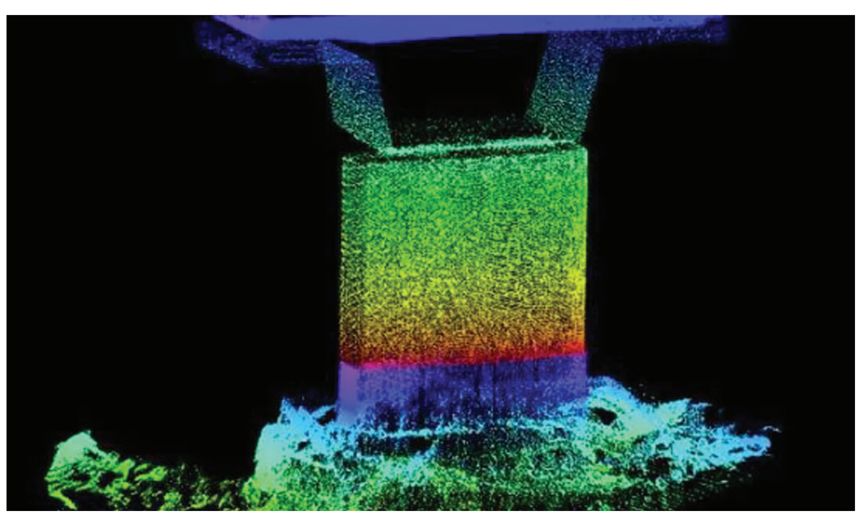
Unlike single beam sonar, which uses just one transducer to map the channel bottom, a multibeam sonar sends out multiple, simultaneous sonar beams from multiple transducers in a fan-shaped pattern. This covers the space both directly under the inspection boat and out to each side. Multibeam sonars interrogate the channel bottom and also collect returns from features that reflect sound in the water column. Water column backscatter data can be used to reveal objects in the water column, including the bridge substructure. Computers on the inspection boat collect and post-process the data to create colorful two- or three-dimensional bathymetric (water depth) maps as well as sonar images of the substructure elements (see Figure 8). As with sector scan, multibeam sonar is frequently used in the underwater bridge inspection industry due to its efficiency and data quality. Multibeam sonar is also used for obtaining bathymetry used for hydraulic modeling, such as SRH-2D modeling, as currently promoted by FHWA.

Volumetric 3D Imaging Sonar

Volumetric 3D imaging sonar is one of the newest, most high-tech sonar technologies available, yielding high-accuracy, high-resolution data images displayed in real time. This technology provides instantaneous 3D images, producing detailed GPS-referenced underwater scans in real time, with comprehensive measurement capability (see Figure 9). This technology also allows for monitoring moving objects underwater in real time (like watching a "sonar movie"), thus allowing monitoring of a diver at work in zero-visibility water. Another key advantage of volumetric 3D sonar is that it offers a more intuitive operation and significantly reduced post-processing time as compared to competing sonar technologies. As with multibeam sonar, volumetric 3D imaging sonar can also be used as an integral part of a hydrographic survey system.

ROV Inspection

Underwater ROV inspection also has roots in the deep-water offshore oil and gas industry. Over the years, however, ROVs have been developed that are



COURTESY: KONGSBERG MARITIME

Figure 8. Multibeam image of bridge pier, showing bottom topography.

COURTESY: CODA OCTOPUS PRODUCTS LTD.

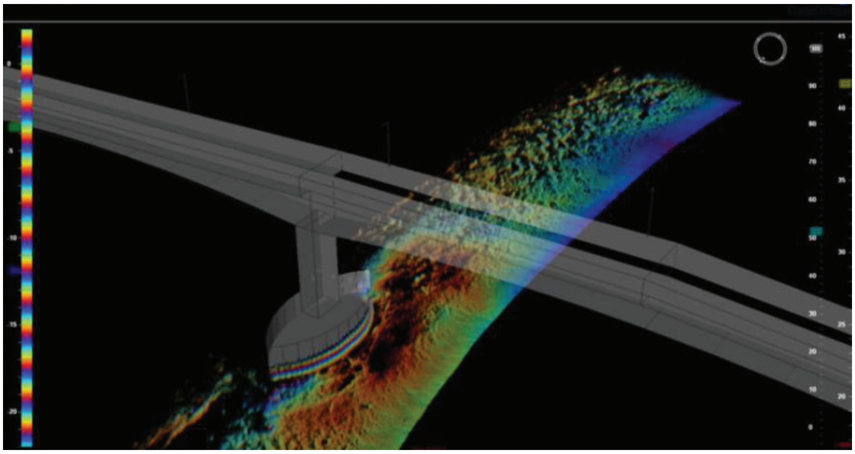


Figure 9. Volumetric 3D sonar image of bridge pier.

COURTESY: RICH ARRIETA, NAVAL INFORMATION WARFARE CENTER

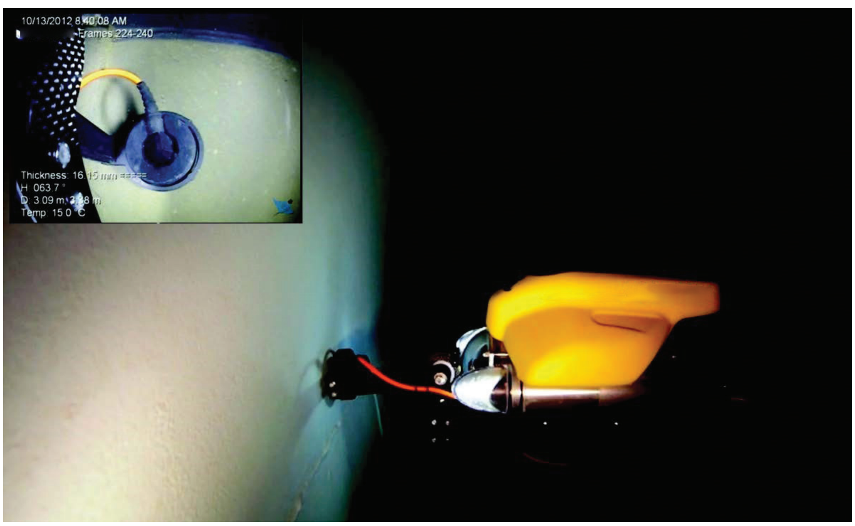


Figure 10. ROV with mounted UTT transducer.

Figure 11. Drift at pier foundation easily detected using sector scanner sonar.

lighter, more agile, and easier and less expensive to own and operate. While early inland-oriented units were primarily "flying photo/video cameras" with limited mobility, today's inspection ROVs are capable of operating against river flow velocities commonly experienced during underwater bridge inspections and employ multiple thrusters oriented to yaw the vehicle into proper position to inspect the element. Today's ROVs are smaller (some less than 12 in. [30.5. cm] in diameter to fit into confined spaces) and offer integral mounting of a sonar imaging head or UTT transducer (see Figure 10). As such, ROVs can be used in lieu of crewed commercial diving for select inspection operations, such as working in polluted waters, or in conjunction with convention diving operations.

Modern Inspection Procedures

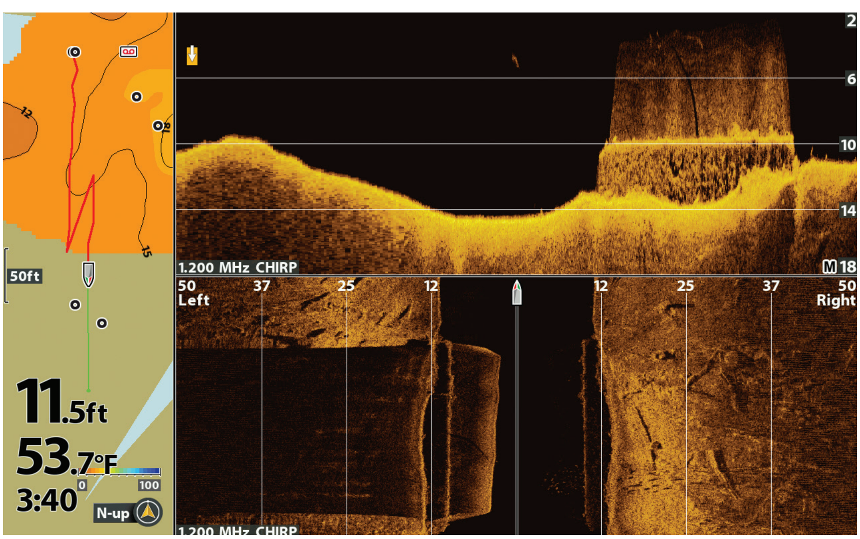
A few scenarios illustrate the benefits of integrating imaging sonar and/or ROVs with conventional diving-based inspection:

- A sector-scanning, multibeam, or volumetric 3D sonar system or sonar-enabled ROV can be used by a dive team to preview piers to evaluate potential hazards, such as drift/debris accumulations, prior to deploying a diver (see Figure 11). This significantly increases inspection efficiency and enhances safety by allowing the dive team to preplan the inspection of each individual bridge pier. Using the appropriate technology, this "pre-inspection sonar scan" can be quickly accomplished as a first step in the inspection process.
- This same sonar system or ROV could then be used to monitor divers' progress and help ensure diver safety during the inspection. With adequate water clarity, the ROV could also provide video of the inspection. This "over-the-shoulder supervision" approach is common practice offshore and allows topside personnel to collaborate with and direct the diver.
- Sonar and ROVs can be used to help evaluate confined spaces, such as areas of foundation undermining,

which by regulation require a minimum five-person dive team to inspect. Considering that underwater inspections are often conducted by an OSHA-compliant, three-person minimum dive team, this approach could help determine the need to revisit only a specific area with a larger crew, rather than staffing the entire inspection with a larger crew. For longer bridges, this may prove especially beneficial.

COURTESY: BRIAN ABBOTT

Figure 12. Sonar attached to bucket truck, to evaluate scour during flood conditions.



COURTESY: HYDRONALIX

Figure 13. Sidescan sonar output from an autonomous vessel during flood conditions.

- Both sonar and ROV technologies may be used during emergencies such as flood events to provide first-response or even mid-event scour assessment (see Figures 12 and 13). The aforementioned autonomous vessel assessment using sidescan sonar provides valuable assistance to the bridge engineer and owner. Similarly, boat-mounted sonar equipment can be deployed immediately after high-flow events or after impact events, to identify damage before a dive team can arrive onsite.

AUTHOR

Dave Severns: Principal - Underwater Inspection Services Lead, Stantec Consulting Services Inc.; 6920 Professional Parkway East, Sarasota, FL 34240; dave.severns@stantec.com

CITATION

Materials Evaluation 81 (1): XX-XX
https://doi.org/10.32548/2023.me-04299

REFERENCES

FHWA. n.d. "Long-Term Bridge Performance." Turner-Fairbank Highway Research Center, Federal Highway Administration (FHWA), fhwa.dot.gov/research/tfhrc/programs/infrastructure/structures/ltbp/.

FHWA. 1995. *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*. Report No. FHWA-PD-96-001. fhwa.dot.gov/bridge/mtguide.pdf.

FHWA. 2018. *Underwater Inspection of Bridge Substructures Using Imaging Technology*. FHWA Technical Report FHWA-HIF-18-049. fhwa.dot.gov/bridge/nbis/hif18049.pdf.

FHWA. 2022a. *National Bridge Inspection Standards*. 23 CFR Part 650. Federal Register 87, (88), Friday, May 6, 2022, Rules and Regulations federalregister.gov/documents/2022/05/06/2022-09512/national-bridge-inspection-standards.

FHWA. 2022b. *Specifications for the National Bridge Inventory*. Publication No. FHWA-HIF-22-017. fhwa.dot.gov/bridge/snbi/snbi_march_2022_publication.pdf.