Guidelines for Underwater Inspection and Imaging of Railroad Bridges

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ABSTRACT

FRA regulations and the AREMA Manual provide some guidance for underwater inspection of railroad bridges; however, no guidance presently exists for underwater imaging, which has been used on hundreds of rail bridges over the past ten years to help ensure the safety of those structures. Therefore, a variety of approaches are currently employed by railroads when it comes to the need and appropriateness for underwater inspection and imaging.

As part of routine inspections, bridges with submerged structural elements are typically inspected by divers who also qualify by training and experience as bridge inspectors. In response to vessel impacts, hurricanes and floods, those same bridges must again be deemed structurally safe, but conditions are often such that it is too hazardous to be accomplished by divers. In such instances, innovative technology is available and has been used in an attempt to assess and document submerged conditions, resulting in bridges either being deemed safe or being closed due to critical findings. This paper provides information on what bridge owners can reasonably expect with underwater images compared to diver observations.

This paper will provide guidance for utilizing underwater imaging technologies as part of underwater bridge inspection and assessment. The paper will also briefly mention the research conducted to date on underwater bridge imaging. Information will be provided on 2-D imaging, 3-D imaging, and various sonar imaging technologies.

1.0 INTRODUCTION

The importance of and need for the underwater inspection of railroad bridges by qualified diving inspectors cannot be overstated, especially in light of the significant age of so many railroad bridges, the recent trend toward severe storms and greater-than-ever high water conditions, and
urbanization that has led to faster runoff with higher velocity flows in waterways where there was little concern in the past. In addition, railroad bridges more often than not have larger, more closely spaced foundations making them particularly vulnerable to scour and other waterway effects that are the leading causes of bridge failures from an underwater standpoint.

The Code of Federal Regulations (49 CFR 213 and 237) requires the underwater inspection of bridge substructures and the surrounding stream bed. In particular, 237(6)b mentions that indirect measurements by sounding, probing, or any other appropriate means are necessary in cases where the stream bed cannot be visibly inspected above water. Additionally, where such indirect measurements do not provide the necessary assurance of foundation integrity, diving inspections should be performed as prescribed by a competent engineer. In the commentary to the 2010 Final Rule of this regulation, the Federal Railroad Administration (FRA) noted that “advanced technology might also provide devices that can be used to determine underwater conditions” and that “a particular frequency for underwater inspections is left to the railroad bridge engineer.”

With regard to the underwater assessment of railway bridges, most railroads that contract for such services, including all of the Class I railroads, do so based on a five-year inspection interval, which is consistent with the maximum interval allowed by the National Bridge Inspection Standards (NBIS) in 23CFR650 Subpart C for the nation’s highway bridges. Although not required by any law—as is the case with highway bridges—railroad companies tend to stick with the five-year maximum inspection interval since it represents the accepted industry standard. Given this inspection frequency scenario, railroads tend to assign a portion of their total inventory of bridges requiring underwater inspection to each year of a five-year inspection cycle. The exception to this is smaller Class II and short line railroads that often opt to inspect their entire inventory at one time every five years, if they proactively schedule inspections at all. As for the procedure requirements that railroads typically stipulate when soliciting underwater inspections, they tend to be less specific than those of their highway agency counterparts. In particular, railroads tend to specify in a more general fashion that the services provided for underwater assessment work shall properly determine what the current underwater conditions are at each particular bridge. This results in the use of a variety of procedures nationwide without any clear-cut guidelines.

Along with the basic requirement to assess current conditions below water, there are often all or any number of the following stipulations expressed by railroads in their requests for underwater services:

- All necessary equipment and personnel shall be provided by the underwater consultant/contractor.
- All applicable federal, state, and local regulations governing underwater work shall be adhered to.
- Visual and/or tactile inspection techniques shall be employed as necessary to properly assess below water conditions.
- Water depth soundings shall be taken to the degree necessary to properly assess channel bottom configuration and its relation to bridge substructure integrity.
- Above and below water photographs shall be taken as necessary to present current specific and typical conditions.
Any conditions requiring immediate concern and/or attention shall be immediately brought to the railroad’s attention.

An assessment report of necessary detail and format to adequately inform the railroad of each bridge’s condition and structural state shall be provided.

Where necessary, the underwater assessment report shall include sketches or figures to adequately depict a bridge’s current conditions.

A concise executive summary identifying the important findings and recommendations for each underwater bridge inspection shall be provided.

In addition to any of the above stipulations, the railroads may or may not require that the underwater inspection work be conducted under the direction of a qualified lead bridge inspector. Furthermore, there may or may not be additional requirements as to whether the lead inspector is to be a professional engineer, and whether that licensed professional engineer needs to be the diver actually performing the inspection(s) or just be topside overseeing the inspection by other divers who may or may not have the desired qualifications stipulated.

When it comes to railroads and their solicitation of underwater bridge inspection services, it seems that there is a tendency to allow considerable latitude with respect to the requirements for the potential inspectors, which probably relates to the fact that the services are primarily selected on a lowest qualified bid basis. In that regard, it appears that as long as the desired end result of condition assessment is met, the lesser constraints placed on the inspectors may allow for lower overall bids for the work. Unfortunately, the owner may not obtain the expected deliverable. In an effort to control costs, some railroads are allowing underwater imaging to be incorporated into the inspection effort, with the thought that it may be possible to limit some of the higher costs associated with diving by substituting the potentially lower cost of underwater imaging. In this regard, it is either stated in some service agreements that underwater acoustic imaging may be used where safety, waterway conditions and/or economics would dictate; or in some instances, underwater imaging is all that is requested with diving being a possible follow-on option, if warranted by the imaging results. With regard to underwater imaging, it is important that the inspector be trained and experienced with sonar; however, few bridge owners mandate demonstrated sonar skills when asking for a proposal.

When underwater imaging is presented as a possible supplement to or a replacement of inspection by diving, there are typically even less, if any, specific requirements as compared to those for a diving inspection. It is sometimes just stated that its use can be considered, as previously indicated, where dictated by project economics or concerns for unsafe and/or very challenging waterway conditions. Furthermore, there is typically no mention of what type of equipment should be used, or what qualifications the operator of the equipment should have when underwater imaging is to be employed at the railroad bridge(s) to be inspected.

Underwater imaging can be accomplished by a variety of optical or acoustic means. Optical means include underwater lasers, but these are not common for underwater bridge inspections. Acoustic means include a plethora of sonar technologies. Therefore, the guidance in this paper focuses on some of the most applicable type of sonar technologies for underwater acoustic imaging, which will be useful to both the bridge owners and the inspection staff considering the options. Just as it is very important that the diver performing an underwater inspection is a
properly qualified bridge inspector, railroads must realize that it is equally important that the
individual performing the underwater imaging at a railroad bridge is properly trained and
qualified, in addition to employing the proper equipment for the specifics of the inspection. In
both cases, the reason is the same—proper inspection qualifications and techniques help to
ensure proper assessment of conditions.

Similar to the FRA position on “any other appropriate means” and mention of “advanced
technology” for underwater inspections, the Federal Highway Administration (FHWA)
Technical Advisory (TA) 5140.21 “Revisions to the NBIS” was issued on September 16, 1988,
and provided guidance on underwater highway bridge inspections. This TA recognized that
technology might advance, leaving the method for underwater bridge inspections open-ended by
stating “inspections in deep water will generally require diving or other appropriate techniques
to determine underwater conditions.” The TA goes on to state that “the underwater inspection
requirements of Title 23 Code of Federal Regulations Section 650.303 pertain to inspections that
require diving or other special methods of equipment.” Although the NBIS and TA 5140.21 do
not specifically state the need for FHWA approval on the type of “special methods” and
“advanced technologies” used to complete an underwater inspection, FHWA concurrence on
methods is required to ensure the “required level of certainty” mandated in TA 5140.21 as part of
their oversight of the highway agency inspection program.

In 2009, the FHWA’s Technical Resource Center responded to highway agencies regarding the
use of acoustic imaging for underwater bridge inspections in an email memo issued by C. Nurmi
stating that Research Study TPF-5 (131) “Underwater Inspection of Bridge Substructures Using
Underwater Imaging Technology” was being planned to assess the use of sonar technology
during bridge inspections. The memo further stated that “the FHWA would address any
policy/guidance or regulatory issues regarding the use or substitution of sonar for underwater
inspections by divers after their research is completed.” Until Research Study TPF-5 (131) has
been completed and FHWA has evaluated the findings, bridge owners were informed that sonar
technology could be used only to supplement bridge inspection diving operations (i.e., to
document findings in conjunction with their Level I and Level II efforts), and in situations where
underwater inspections cannot be safely performed by divers since some information is better
than no information. However, the memo clearly stated that sonar results alone are not allowed
as a substitute for the data obtained by a qualified diving inspector with the appropriate intensity
levels, as outlined by FHWA guidelines. Therefore, the ongoing research study TPF-5(131) was
aimed at studying the effectiveness of acoustic imaging technologies for underwater inspection
of bridges by clarifying the quality, accuracy, and repeatability of data that commercially-
available acoustic imaging devices are capable of producing and by demonstrating how this data
compares with inspection findings documented by a qualified underwater inspection diver. In the
meanwhile, some bridge owners have developed their own policies on underwater imaging. The
Illinois Department of Transportation (IDOT) allows underwater acoustic imaging to be
performed at unsafe sites to preliminarily evaluate the bridge until divers can enter the water.
The IDOT Structural Services Manual Table 3.3.4.5 provides some imaging guidance (such as
mandating only three allowable sonar technologies) and criteria for defining safe conditions for
routine diving inspections based on their risk assessment methodology.
There are also numerous publications and training courses by FHWA and others related to underwater bridge inspection, scour detection, scour evaluation, and scour repair design; but no additional formal guidance on the use of acoustic imaging at bridges.

In the past, studies have been conducted on the reliability of bridge inspection techniques, and various research projects have investigated the possible integration of advanced technologies into the activities for structural inspections above and below water. However, these efforts have been selective and not comprehensive. Nonetheless, much interest has been shown by several state highway agencies and a host of security related agencies, including the Department of Homeland Security (DHS), United States Geological Survey (USGS), Federal Bureau of Investigation (FBI), and National Oceanic and Atmospheric Administration (NOAA), for the implementation of underwater observation technologies.

2.0 UNDERWATER IMAGING TECHNIQUES AND SPECIFICATIONS

Underwater imaging is a general concept that encompasses a wide variety of technologies. Underwater photography and underwater videography are the two most commonly used methods for obtaining underwater images. However, water clarity greatly affects the quality of the images obtained by these two optical means. Furthermore, the camera range and lighting for underwater photography and videography often prohibit a large panoramic view, and only providing a two-dimensional (2-D) perspective. Non-optical technologies that have demonstrated success in providing underwater images include sonar, laser, and radar.

Laser scanning (often referred to as Lidar in above-water applications) can produce extremely accurate underwater images but possesses limited range due to light transmission factors related to water clarity. This and other limitations make it more widely used for offshore ocean structures than inland waterway bridges.

Radar technologies, such as ground penetrating radar (GPR), can produce underwater images primarily of internal concrete defects or subsurface channel-bottom geotechnical strata layers, while synthetic aperture radar (SAR) has been used to obtain large-area perspective underwater imaging of channel-bottom topography.

Of all the non-optical underwater imaging technologies, sonar has demonstrated the most potential and is the most widely used for bridge inspection applications. Even in the most turbid waters with zero visibility, sonar can provide water depth data and high-quality images. Since sonar technology utilizes sound waves, it is known as an acoustic technology. Underwater acoustic images vary in quality, resolution, and dimensional perspective (2-D or 3-D) depending on the particular sonar device.

Sonar technologies can be classified into two broad categories based on the type of data that they produce. Some systems produce two-dimensional data while others produce three-dimensional data. Two-dimensional sonar systems take a three-dimensional space and plot it on a two-dimensional screen. Two-dimensional sonar produces the best definition when the angle of incidence is very high.
Three-dimensional data consists of many data points each with unique x, y, and z coordinates. There will always be some amount of interpolation between data points in a rendered sonar image. When discussing three-dimensional data such as that produced by single or multi-beam sonar, the amount of detail that can be generated is dependent upon how small an area the beam can focus on to obtain a point reading, and also upon the number of points that are obtained. The number of data points obtained in an area is referred to as data density. If a particular sonar system has more beams, or a faster ping rate, the ability to obtain more dense data coverage becomes possible in less time. Three-dimensional sonar works best when the angle of incidence is very low.

3.0 THREE-DIMENSIONAL SONAR SYSTEMS
Fathometers/Echosounders

For bridge inspections, water depths can be manually obtained with a sounding pole or lead line, but sonar devices provide more efficiently and effectively retrieved electronic data. The simplest fathometers consist of an acoustic sending/receiving device (transducer) suspended in the water and a digital or paper recording device. Paper strip-chart recorders used by recreational fishermen have long been an adapted inspection tool for bridge managers due to its permanent “hard-copy” documentation capability. However, these inexpensive strip-chart recorders are being phased out and replaced by more modern survey-grade precision echosounders.

Fathometers and echosounders are single-beam sonar systems that gather three-dimensional data when connected to a GPS or other geographical coordinate collection system. Fathometer frequencies typically range between 24 kHz and 340 kHz, with higher frequencies yielding higher resolution, but little or no channel-bottom penetration. Because channel-bottom penetration is typically not desired when performing a fathometer survey, a higher frequency of 200 kHz is commonly used.

More advanced fathometer systems are compatible with GPS receivers or robotic total stations and allow geographic coordinates to be associated with each depth reading. When a fathometer is coupled with one of these devices, water depths can be post-processed and referenced to a state plane or other horizontal coordinate system. This allows for very accurate channel-bottom surveys, which can be easily compared to future surveys. When water conditions allow, a boat-mounted transducer allows efficient data collection. However, transducers mounted on poles, floats, or articulated arms have been used when maneuvering a boat is unfeasible due to high flows.

A fathometer survey conducted during a typical underwater inspection may include recording channel-bottom profiles along the bridge fascias, as well as 100 and 200 feet upstream and downstream of the bridge. However, some bridge owners obtain significantly more data for a complete hydrographic survey on certain waterways. Figure 1 illustrates a typical contour map of a bridge site showing scour around the piers. The figure was produced using single-beam sonar data.
Advantages/Limitations of Fathometers and Echosounders

The primary benefit of a fathometer is the ability to obtain geo-referenced channel-bottom profiles. The profiles can be used to locate and quantify apparent scour depressions, areas of aggradation, and channel-bottom objects such as exposed pier footings or debris accumulation. Overlaying and comparing channel-bottom profiles from successive underwater bridge inspections can alert engineers to possible channel-related problems. Bridge foundation information from as-built plans can be superimposed onto the channel cross-sections and profiles for reference purposes.

The primary limitation of a fathometer is its inability to collect data outside the path of the vessel transporting the transducer. For this reason, the functionality of fathometers is limited to obtaining channel-bottom depth information only and imaging of vertical structure faces is not practical.

Because sonar footprints can become quite large at depth, the sonar operator must be careful not to confuse an exposed bridge footing or other submerged obstruction with the channel bottom. With single-beam sonar, the exact location of the return echo is not always known. Figure 2 illustrates a likely scenario for obtaining a false return echo near a bridge pier. Likewise, fathometers will not provide information about the channel-bottom elevation located directly below a footing and cannot provide undermining dimensions.
Data density is typically low in comparison to data obtained by multi-beam sonar collection methods. For instance, a single-beam fathometer survey will typically cover only 5 to 10 percent of the total channel-bottom area. This limitation prevents detection of channel-bottom irregularities or scour holes unless the vessel passes directly over the top of the area in question with a narrow beam. Additionally, contour maps created from single-beam sonar rely heavily on interpolation between data points. In other words, data obtained from these systems don’t possess high enough resolution to detect small irregularities. For channel bottoms that are relatively flat, or that have a gentle slope, this method works well. Low data density and the presence of steep or irregular surfaces can cause data interpolation to show an inaccurate representation of actual conditions.

**Multi-Beam Swath Sonar**

Multi-beam swath sonar was first developed by SeaBeam Instruments in the mid 1960s for the U.S. Navy. Multi-beam swath sonar consists of a line of numerous narrow circular beams as indicated in Figure 3. The beam arrangement allows detailed mapping of a very thin transverse section with each sonar pulse. Most systems are boat mounted and require forward progress of the boat to advance the position of the send/receive signal. Operating frequencies usually range between 0.7 MHz and 1.8 MHz. Other multi-beam swath systems are setup with extremely low frequencies for sub-bottom profiling applications.

Multi-beam sonar systems, also referred to as swath echosounders, function similarly to single-beam echo sounders except they have multiple sonar beams acting simultaneously allowing for much denser data coverage in a shorter period of time. This type of system uses a fanned array of sound beams that typically give near 100 percent coverage of the seafloor or channel bottom. For
instance, a typical multi-beam survey may have a fanned array that is capable of a “swath width” of seven times the water depth. This means that if the water is 100 ft deep, bathymetric data can be obtained up to a swath of 700 ft wide, or 350 ft to the port or starboard side of the survey vessel. For vertical imaging applications, the same theory applies but the swath width is dependent upon the distance between the transducer and the pier face. Since the direction and angle of the beams can change with the heave, pitch, and roll of the survey vessel, it is necessary to have motion compensators and a gyrocompass that account (in real-time) for the motion and relay correction factors back to the on-board processor.

Another form of multi-beam sonar is three-dimensional mechanical scanning sonar, which is essentially a multi-beam sonar unit fitted with a mechanical stepping motor. The sonar needs to remain stationary while performing scans.

![Figure 3. Multi-beam swath sonar beam pattern.](image)

**Advantages/Limitations of Multi-Beam Swath Sonar**

The primary benefit of multi-beam swath sonar is the ability to quickly obtain large quantities of three-dimensional data. Multi-beam swath sonar produces a three-dimensional still image that is often referred to as a point cloud. For bridge inspection applications, the production of three-dimensional data would allow an inspector to document and assess the depth of spalling, scaling, or possibly even foundation undermining. By using multiple or overlapping passes, the sonar operator is able to obtain greater data density and 100 percent bottom coverage of the area.

The primary limitations of multi-beam swath sonar are that the vast quantities of data produced can be cumbersome and time consuming to post process. Because of the additional sensors required and the complexity of the relationship between these sensors, a portable multi-beam installation is significantly more complex and time consuming than a comparable single-beam installation. Both field operation and data post processing require a greater deal of training and
skill to master than other imaging sonars used without motion compensation or GPS positioning. Additionally, multi-beam sonar systems are considerably more expensive than other products.

The final limitation of multi-beam sonar as it pertains to bridge inspection is the difficulty of such systems to smoothly transition from acquiring data from the channel to the vertical face of a bridge support when they are in a downward looking configuration. This occurs because multi-beam systems are finely tuned through power and gain adjustments to detect the channel bottom and thus don’t always accurately record returns from dissimilar materials and locations. Additionally, the data often requires a large amount of manual post processing to weed out the acoustic noise. In the hands of a skilled technician, multi-beam swath sonar can yield high quality surveys but the relative complexity compared to single-beam systems is a definite reason it is not frequently used at railroad bridges. It should also be noted that multi-beam systems would be a poor choice for shallow waterways with relatively simple bottom topography. However, in areas with certain environmental characteristics (e.g., deeper water, complex bottom topography, limited visibility, strong currents, etc.) multi-beam surveying offers a number of unique benefits relative to any other existing technologies.

Real-Time Multi-Beam Sonar

Real-time multi-beam sonar is a modified version of multi-beam swath sonar. Instead of using a single line of narrow beams, it contains many rows and columns of narrow beams that ensonify a volume, allowing for more dense data coverage. For example, thousands of data points are created with a single ping as opposed to hundreds with traditional swath multi-beam systems. These systems create three-dimensional images that are updated in real-time, similar to watching a video and they can be mounted on a vessel, ROV/AUV or fixed installation. Figure 4 illustrates the beam pattern of a typical real-time multi-beam sonar system.

Figure 4. Real-time multi-beam sonar beam pattern.
**Advantages/Limitations of Real-Time Multi-Beam sonar**

There are many advantages when using real-time multi-beam sonar systems. Real-time multi-beam sonar provides the benefits of 3-D data but unlike traditional multi-beam systems, some can be rapidly deployed and require less special operator skills, training, and post processing. Due to the large number of beams and high data density, large and complex structures can be covered quickly without the need for multiple passes. The end result is greatly increased productivity.

Because a single geo-referenced point on an object being scanned is continuously ensonified from different angles as the platform moves, multipath error can be reduced by software algorithms that track whether objects remain stationary between consecutive pings. This produces datasets with less acoustic noise. Another advantage to continuously scanning each object from multiple angles is that the dataset produced has less acoustic shadows resulting in fewer unknowns from the dataset.

Real-time multi-beam sonar systems have the same limitations as swath multi-beam. Another limitation is that although real-time multi-beam sonar systems can be used as a “stand alone” unit, they still need to be fully geo-referenced using GPS and motion compensating devices for the best results. This adds an extra level of cost to an already expensive sonar system and creates more equipment to maintain.

### 4.0 TWO-DIMENSIONAL IMAGING SONAR

Two-dimensional imaging sonar systems have oblong, fan-shaped beams. They essentially work by recording the full range of returns from the wide dimension of the cone angle and plotting them on a two-dimensional drawing. The sonar unit can’t distinguish which portion of the wide cone angle a return came from but it can tell if an echo returns from more than one distance. Figures 5, 6, and 7 illustrate the orientation of sector scanning sonar’s fan beam to produce a plan view image; a section cut image, and an elevation view of the pier face respectively. The same beam orientations are used to produce similar images with other two-dimensional sonar devices such as side scan sonar and lens-based multi-beam sonar.
Figure 5. Orientation of fan beam to produce a plan view image.

Figure 6. Orientation of fan beam to produce a section cut image.
Side-Scan Sonar

Side-scan sonar was first introduced in the early 1960s and has been successfully used for documenting underwater findings for many years. Side-scan sonar operating frequencies usually range between 83 kHz and 800 kHz. Side-scan sonar works by emitting fan-shaped acoustic pulses through the water column. The beam is narrow in one plane (typically less than 1°) and wide in the other plane (typically between 35° and 60°). Figure 8 shows the shape of a typical side-scan sonar beam and step spacing. The transducer is either towed behind a boat or mounted on the transom or hull of the vessel. Side-scan sonar requires the boat to have forward progress so each successive sonar ping will be positioned slightly in front of the previous. The resulting images from the channel bottom and objects located on the bottom or in the water column are representative of the echoed (backscattered) target intensity within the geometric coverage of the beam. When the images are stitched together along the direction of travel, they form a contiguous image of the bottom and objects located on the bottom or in the water column.
Advantages/Limitations of Side-Scan Sonar

The primary benefit of side-scan sonar is the ability to quickly and efficiently generate images of large areas of the channel bottom. For this reason, side-scan sonar is considered the tool of choice for large-scale search operations. Side-scan sonar can be used for many purposes, including delineation of exposed sediment and geologic formations, detection of underwater debris or objects that may be hazardous to marine operations and searching for shipwrecks. In addition, the general location and configuration of submerged structures, pipelines, and cables can be investigated using side-scan sonar.

The primary limitation of side-scan sonar is the inability to easily generate full images of the vertical components of submerged structures. It is possible to image portions of vertical components of bridge substructures with side-scan sonar; however, the transducers must be rotated 90 degrees and pole-mounted. The quality of the image that results is largely dependent on the operator’s ability to maintain a close and constant distance to the pier face and maintain a constant speed while driving the boat past the bridge pier. Some newer recreational fathometers now also have a side-scan view, but these units are typically more useful for fishing than anything related to structural assessments.

As a result, sector-scanning or multi-beam sonar are generally considered better solutions for generating images of the vertical components of submerged structures. Other limitations to side-scan sonar include: the inability to maintain step size and thus detect narrow linear targets parallel to the beams; difficulty keeping the towfish at a constant location behind the vessel and
at a constant elevation in the water column; keeping the vessel along a consistent line at a constant speed; and vessel pitch and roll, especially if using a hull-mounted application.

**Sector-Scanning Sonar**

The first known use of sector-scanning sonar for a bridge assessment was conducted by Collins Engineers, Inc. in the early 1990s. Although scanning sonar was used to investigate submerged structures more than 20 years ago, it was not until circa 2000 that higher resolution imaging devices became readily available at cost effective prices. Since 2000, numerous bridges have been scanned to document underwater conditions.

Scanning sonar works similarly to side-scan sonar in that the transducer emits fan-shaped acoustic pulses through the water; however, unlike side-scan sonar, which requires vessel movement to develop an image, scanning sonar works best if the transducer remains stationary while the head is mechanically rotating. The acoustic images are recorded in a series of “slices” generated by a ping after each rotation of the transducer. Scanning sonar operating frequencies usually range between 330 kHz and 2.25 MHz, with a common frequency used for channel bottom and structural imaging of 675 kHz. Figure 9 shows the fan-shaped beam and scanning pattern produced by typical sector-scanning sonar.

![Figure 9. Sector-scanning sonar beam shape and step pattern.](image)

**Advantages/Limitations of Sector-Scanning Sonar**

The primary benefit of scanning sonar is the ability to produce detailed images of the channel bottom and vertical components of submerged structures that extend from the channel bottom to the water surface. Scanning sonar can also be used prior to and during diving operations to direct
the underwater inspector to potential deficiencies, as well as direct the inspector around potential below-water hazards. Sector scanning of vertical structure surfaces typically does not require geo-referencing thus simplifying the process.

Due to limited range and the need for the sonar head to be located in a stable mounting position, the primary limitation of scanning sonar is that stationary setups require greater time to obtain. Additionally, developing highly detailed images using scanning sonar is heavily dependent on sonar positioning and stability.

5.0 SUITABILITY OF TECHNOLOGY FOR APPLICATIONS

The requirements for underwater bridge inspection procedures are well documented. Yet some bridge inspectors and owners have increasingly been turning to acoustic imaging technology to enhance inspection and documentation procedures. This trend has been accelerated based on the special needs of some bridge owners with a large number of bridges containing adverse site conditions such as zero visibility, high velocity currents, heavy debris, and extreme depth. Because these factors can limit a diver’s ability to thoroughly inspect a bridge below water, enhancements such as acoustic imaging have been used as a supplement to ensure a thorough inspection. Potential applicability of acoustic imaging for bridge inspections are outlined in the below sections:

- Rapid condition assessment
- Scour detection and documentation
- Underwater construction inspection
- Enhancing diver safety and efficiency at challenging dive sites

It should be noted that potential applications exist for security threat detection/assessment and documented visual representation for structural modeling integration, but those topics are not covered herein.

Rapid Condition Assessment

Both natural disaster and man-made events can cause the need for emergency structural assessment. Natural disaster events include hurricanes, tornadoes, floods, earthquakes, and tsunamis. Man-made events can include vessel or vehicle impacts and dam breaks. Rapid condition assessment is often required immediately following an emergency event.

Emergency events can threaten the structural stability of a bridge, and decisions often cannot wait for adverse conditions to become more favorable for an underwater inspection. The immediate need for a bridge closure decision can result in overly conservative closure delaying passenger or freight travel. With acoustic imaging technology, bridge owners can get important information about a structure during or soon after an event, whereas a dive inspection might have to wait weeks or months for floodwaters to recede or for conditions to otherwise become favorable.
Scour Detection and Documentation

The number one cause of bridge failure in the United States is scour. This makes it of paramount importance for bridge owners to be able to efficiently and safely assess the presence of scour at a bridge site. While national data is not available for railway bridges, it is known that over 7,500 highway bridges are deemed “scour critical,” according to the 2011 data. The presence of scour can often be difficult for an inspection diver to detect for a variety of reasons and this makes underwater imaging technologies extremely useful.

In addition to hydrographic surveys, fixed scour monitoring systems can be established for continuous scour monitoring at a specific site. A fixed scour monitoring system means that it is permanently or semi-permanently attached to a structure to repeatedly monitor a specific area. According to the Transportation Research Board, in 2009 over 30 highway agencies had fixed scour monitoring installations and over 60 of those installations utilized at least one sonar system.
Figure 11. Mutibeam sonar image of undermined bridge substructure units.

Figure 12. Sector scanning sonar image of embankment slope erosion.
Underwater Construction Inspection

Underwater imaging technologies can be used in all phases of construction, from pre-construction planning, through the construction phase, to verifying as-built information. Figure 13 provides an example of 3-D imaging used in the placement of grout bags.

![Mutibeam sonar image of repaired bridge undermining with grout bags.](image)

Figure 13. Mutibeam sonar image of repaired bridge undermining with grout bags.

Enhancing Diver Safety and Efficiency

As described in the cases above, underwater imaging technology has a large impact on diver safety and efficiency. As previously stated, many acoustic imaging technologies have the ability to generate data that can then be used to track a diver’s location or direct a diver to or away from a specific area. Figure 14 shows a sector scanning image of a bridge pier with a surface supplied air diver walking on the channel bottom in the foreground.
6.0 ATTRIBUTES RELATED TO QUALITY DATA
Construction Materials & Associated Defects

The underwater portions of a structure are generally subject to similar types of distress and deterioration based on the construction materials used. The characteristics of a construction material will influence the quality of an acoustic image and the ability to detect certain defects based on surface texture and differing acoustic absorption coefficients. Because acoustic imaging methods do not provide a definitive identification of submerged construction material type, consultation of as-built bridge plans is recommended to aid in the analysis of acoustic imaging results. The most common bridge construction materials and defects associated with each are discussed below.

Masonry is very common in older railway bridges. Typical problems found in masonry structures include missing stones, cracking, scaling, and deteriorated grout.

Three types of concrete bridge elements include unreinforced, reinforced, and pre-stressed members. The compressive strength of concrete commonly used in bridges varies from 3 to 11 kips per square inch (ksi). This variance in material density may provide differing acoustic reflectivity properties. There are three main categories of concrete defects:

- **Cracking**—Because concrete has little tensile strength, cracks occur due to volume changes as temperatures vary and a concrete member contracts or expands. Cracks may be due to structural and non-structural causes. Cracks may also be an indication of overloading, corrosion of the reinforcing steel, or settlement of the structure. Acoustic
imaging has successfully documented cracks underwater, especially with wider widths or any offset surface alignment, but smaller cracks are likely not to be detected in such an image.

- **Scaling**—Scaling is a gradual and continuous loss of surface mortar and aggregate from an area. This condition is commonly found at the waterline on piers and piles where freeze-thaw action occurs. Acoustic imaging will usually not differentiate minor section loss due to scaling depending on the technology.

- **Spalling**—Spalling is a delamination or fragmented void in the surface of concrete which typically exposes corroded reinforcing steel. It is primarily the result of internal expansive forces caused by corrosion of the steel. Similar to scaling, only larger spalls will be visually noticeable on a sector scanning sonar image or a multibeam image. However, only multibeam sonar will typically highlight the penetration for volume calculation ability in addition to the surface size of the deterioration.

Steel is used as a structural material for piling and bracing and as external protective cladding on concrete elements. The primary cause of damage to steel is corrosion. Corrosion is most prevalent in the splash and tidal zones, but can occur both above and below water. The corrosion can be especially severe when the bridge is located in salt water or brackish water. The most important factors influencing and producing corrosion are the presence of oxygen, moisture, chemicals, pollution, stray electrical currents, certain microbes, and water velocity. Heavy marine growth, found in seawater, can sometimes inhibit corrosion, but it can also hide severe distress. Steel coatings are commonly used to prevent corrosion. The underwater inspection of coated steel structural members should also assess deterioration of the coating. However, useful acoustic images are often difficult to obtain in areas with heavy marine growth and coating evaluation with imaging is not feasible.

Deterioration in timber members results from a variety of sources, including decay, marine infestation, bacterial degradation, abrasion, and collision. For acoustic imaging purposes, varying densities and saturation levels of timber may affect imaging results. Hence, the reason many timber piles are only partially captured on images in some cases. It is important that the inspector understand this challenge so as not to literally interpret the image to indicate that missing sections exist in the timber piles.

Composites, or fiber reinforced polymers (FRP), are a mixture of fibers and resins. Most mechanical defects of composite materials are due to impact and abrasion, or construction related events. Composites are susceptible to fire and to degradation by exposure to ultraviolet rays, and are more resistant to marine borers than timber members.

**Geometric Configuration**

For both structural and architectural reasons, there are many variations of bridge substructures in existence today. Long slender members are visually more affected by sonar distortions which can cause members to appear bent or buckled when they are actually straight.
Environmental Influences

Environmental factors that may influence imaging of a particular bridge include water temperature, salinity, and depth. Assuming that the sonar device being used has the appropriate feature, these factors can be easily accounted for based on calibration of the equipment with regards to the local speed of sound. Owners should require their inspectors to utilize a water sound velocity meter and calibrate their equipment for the best quality results.

Additional environmental factors include:

- Turbidity level—may affect results produced by certain sonar frequencies. However, this is seldom a reason for not obtaining a quality image since even the muddiest rivers in America with no underwater visibility have yielded usable quality images.
- Current—may affect the method of and ability to securely deploy the sonar head to reduce heave, roll, pitch, and yaw. Very fast current (> 6 fps) and floating debris / ice are common challenges that most skilled operators can overcome to obtain quality images.
- Marine growth, which may obstruct sound waves from reaching the surface being imaged. The amount and consistency of marine growth may cause slight resolution distortion issues, but usable quality overall images are often possible.
- Turbulence—air bubbles suspended in the water column. Since sonar uses sound waves traveling through the water, eddies and rapids with significant air bubble formations near a bridge may limit the ability to collect sonar data.
- Depth—very deep water may result in images with poor resolution and very shallow water may present sonar deployment issues and multipath errors. However, a skilled operator can easily assess the feasibility of obtaining quality images at a site based on water depth knowledge and equipment availability.

7.0 CONCLUSIONS

As railroads consider their options and what to require when it comes to underwater bridge inspections—in particular, the use of underwater imaging—there needs to be careful consideration for assuring proper inspector credentials, proper equipment and inspection techniques, and simply knowing when underwater imaging is suitable and appropriate for underwater bridge condition assessment. Underwater acoustic imaging has been deemed extremely valuable during emergency inspections when a diver could not enter the water. Furthermore, the images obtained from this technology during routine underwater inspections have benefited the divers and bridge owners. However, there are often challenges to determining the most appropriate equipment for an individual site. With the appropriate equipment, which typically for bridge inspections utilizes sector scanning sonar or some type of multibeam sonar, quality high definition images are often possible. In some circumstances, environmental conditions, material attributes, or geometric configuration may prevent the highest quality of image, although the skill of the operator is often a major factor. Because of this, it is important that an underwater imaging sonar operator be trained and experienced so that the bridge owner obtains an accurate assessment and quality image. With all images, this information can prove
maritime transportation vessels’ accountability for damage due to impacts, as well as assist in reducing risk/liability of the railroad company operating on the bridge.

REFERENCES


FIGURES

Figure 1. Typical single-beam hydrographic survey plan of a bridge site.
Figure 2. Example of a false sonar echo return near a bridge pier.
Figure 3. Multi-beam swath sonar beam pattern.
Figure 4. Real-time multi-beam sonar beam pattern.
Figure 5. Orientation of fan beam to produce a plan view image.
Figure 6. Orientation of fan beam to produce a section cut image.
Figure 7. Orientation of fan beam to produce an elevation view image.
Figure 8. Side-scan sonar beam shape and step pattern.
Figure 9. Sector-scanning sonar beam shape and step pattern.
Figure 10. Sector-scanning sonar image of bridge pier and capsized barge due to impact.
Figure 11. Mutibeam sonar image of undermined bridge substructure units.
Figure 12. Sector scanning sonar image of embankment slope erosion.
Figure 13. Mutibeam sonar image of repaired bridge undermining with grout bags.
Figure 14. Sector scanning sonar image of diver conducting bridge inspection.
Guidelines for Underwater Inspection and Imaging of Railroad Bridges

Dan Stromberg, Collins Engineers, Inc.
Terry Browne, Collins Engineers, Inc.
How common are scour issues at bridges?

- #1 Cause of bridge failures
- Numerous issues occur every year

Dilemma exists when floods prevent divers

- “current too fast”
- “so murky, you couldn’t inspect”
- “jeopardizing commerce to hold trains until divers”

Presentation Agenda

- Underwater Inspection Guidance
- Underwater Imaging Technologies
- Applications of Technology
- Assuring Quality
- Conclusions

Overview of Regulations / Guidance in USA

- 49 CFR 213
- 49 CFR 237
- AREMA Manual
- U.S.D.O.T. Underwater Bridge Inspection Manual

Underwater Inspection Procedures

- Railroad internal policies vary
- Techniques familiar to personnel vary
- Training for underwater inspectors vary

Scour evaluations and UW inspections

- Scour evaluations are recommended and must be updated
- Underwater inspections are required and must be conducted as needed
Underwater Inspection Methods
- Wading
- Diving
- Advanced Technology Techniques

Wading Inspection Limitations
- Slow flow or no current
- Three foot maximum water depth
- Two-person team minimum
- Other considerations

Inspection by Diving (Self-Contained & Surface-Supplied)
- Both methods permitted by OSHA
- Both methods have a place in bridge inspection
- Selection depends on various factors:
  - Water depth / bottom time
  - Diver experience/capabilities
  - Type of waterway / environment

Self-Contained Diving (Scuba) Inspection Limitations
- Limited breathing gas supply
- Min. 3-person team
- Max. water depth of 130 ft
- Tethered if >1 knot or penetration

Surface-Supplied Diving Inspection Advantages
- “Unlimited” breathing gas supply
- Tether and communications inherent
- Better isolation from water

Surface-Supplied Diving Inspection Limitations
- Min. 3-person team
- Max. water depth of 220 ft (air)
- Practical current limit of 2.5 knots
- Limited maneuverability and mobility
Advance Technology Techniques for Underwater Inspections

- Remotely operated vehicle (ROV)
- Electronic video inspection device (EVID)
- Imaging systems

Lens-Based Sonar as a Scour Inspection Technique

- Distance from diver to object
- Diver held transducer
- Undetermined bridge footing with exposed piles

Risk can be managed with Information

- Information sources
  - Contract documents
  - Diver inspections
  - Sonar bathy survey data
  - Underwater imaging
    - 2-D images
    - 3-D point cloud models

Overview of Sonar Technologies

- Sonar/acoustic methods
  - Single-beam
  - Side scan
  - Sector scanning
  - Multi-beam (swath or tripod)
  - Real-time multi-beam

Single-Beam Sonar

- Basic survey
  - Provides general representation of channel bottom features
Single-Beam Sonar

- Low data density
- Useful visualization
- Documentation, but not imaging for observations

Sector-Scanning Sonar

- Sonar head must remain stable

Scanning Sonar During Post Event Inspection

- Timber Debris

Scanning Sonar as a Scour Inspection Technique

- Exposed Footing
- Channel Bottom

Sector Scanning Sonar
### Sector-Scanning Sonar

**Advantages**
- Easy to use
- Adaptable to imaging of vertical surfaces

**Disadvantages**
- Does not provide 3-D data (product is similar to black and white photograph)

### Side-Scan Sonar

- Emits fan shaped acoustic pulses
- Product is similar to a b/w photo in plan view

### Side Scan Sonar

**Advantages**
- Covers large area quickly (Coverage area increases with depth)
- Ideal for search and recovery (e.g. shipwrecks)

**Disadvantages**
- Does not provide depth data (Product is similar to black and white photograph)
- Not easily adaptable to vertical surfaces

### Swath Multi-Beam Sonar

- Emits multiple beam pulses
- Point cloud data product

**Advantages**
- Provides good accuracy and complete coverage
- Quickly obtain large quantities of data
- Can be used for structural imaging as well as hydrographic surveying

**Disadvantages**
- System is typically large and bulky... requires 20 ft+ boat with enclosed cabin
- Expensive (extra sensors for all motion related errors)
- Requires advanced land survey and drafting skills
Mechanical Scanning Multi-Beam Sonar

- Produces highly detailed images of underwater surfaces

Advantages
- More customizable head positioning for undermined, overhanging, or enclosed surfaces (e.g., diver deployed)

Disadvantages
- Post processing and data registration are very time consuming and require a high level of skill and experience
Conclusions

- Technology is available to allow safe and economical underwater investigations (even during floods); however, the most appropriate system needs to be utilized.

- Underwater inspectors and imaging specialists should have proper training and experience for applications.