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Final Report to

Leroy Arnold  
Little Rock District, U.S. Army Corps of Engineers  
700 West Capitol  
Little Rock, AR 72203-0867

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# **Underwater Full Wavefield Seismic Investigation for Voids under the Spillway Stilling Basin of Hardin Dam #3 on the Arkansas River**

## **Executive Summary**

Water-bottom seismic data acquired immediately downstream of Gate #1 at Hardin Dam #3 located on the Arkansas River near Pine Bluff, Arkansas, proved simultaneously instructive, encouraging, and unsuccessful. A key goal of the survey was to delineate the suspected void located beneath the stilling basin around Gate 1 and to delineate the extent and origin of known dam-foundation degradation between Gate 1 and about Gate 7. The original research plan was to acquire and analyze surface waves from atop the concrete slab at the bottom of the stilling basin. Surface-wave seismic profiles were to be collected parallel to the axis of the dam, targeting areas with suspected sub-slab anomalous materials. Considering this was the first time such a survey had been attempted, several adaptations and developments were needed to efficiently generate and record surface-wave arrivals suitable for dispersion, backscatter, and inversion analysis.

Hydrophones were deployed along the bottom of the stilling basin with boat anchors and floats used to hold the hydrophone in place and locate the ends of the receiving cable. A two-boat configuration was used to attempt the acquisition—one was the source and receiver boat and the second was set up for recording data. The recording boat was secured to the side of the dam, while the source/receiver boat was free to maneuver parallel to the dam axis and directly over the concrete-lined stilling basin. Water flow measured at between 20k and 30k cfs inhibited the ability of the source/receiver boat to maintain a stable position long enough to detonate the source into a static cable position. Test data were finally acquired using the two-boat configuration as a barge, deploying the receiver spread on the bottom of the Gate 1 stilling basin and secured to the side of the two boats. The sources were detonated at different locations along the side of the boats, providing a data set that simulated a walkaway noise survey.

Shot gathers possessed arrival patterns characteristic of voids as observed at several sites with culverts, tunnels, and fault/fractures on land seismic data. This anomaly is interpreted on shot gathers to possess a curvature with apex near receiver 15, or approximately 10 stations from the source. Based on the interpreted shape of the seismic arrival returning from this anomaly, it appears to be around 8 to 10 ft below the top of the concrete slab and directly beneath the hydrophones' locations at a spot about midway along the hull of the rear boat in the two-boat configuration being used as a work platform. This seismic return could be from any one of several different types of anomalous features (anomalous to a normal layered earth). Included on that list are man-made foundation structures, voids, out-of-the-plane scatterers, boulders, construction fill, etc. It is however similar to model representations of voids and/or tunnels.

Improving interpretation using these data requires an improved spatial focusing of the source, which is unlikely with this data set considering the limited number of source locations that were occupied. With all the structures and abrupt changes in velocity/density likely present beneath the slab in this immediate area, the exact source of this “scattered seismic energy” cannot be determined uniquely. It is likely the interpretive confidence with these data could have been dramatically improved if we had collected a continuous line, where source and receivers moved from areas with known voids to areas known to be without voids. A data set of that type would have provided the necessary template for characterizing what these target voids look like on these kinds of seismic data.

## Introduction

Navigation on the Arkansas River between Little Rock and the convergence of the Arkansas and Mississippi rivers totally depends on a well-developed dam and lock system built, managed, and maintained by the U.S. Army Corps of Engineers, Little Rock Division. Foundation distress on Hardin Dam #3 near Pine Bluff, Arkansas (Figure 1), has been inferred from measurements and observations (Arnold, 2007):

- Void in the vicinity of Gate 1, beneath the stilling basin
- During the July 2004 pressure-relief system pump test, pump discharge did not clear of discoloration; i.e., sand present!
- Void size is undefined; may extend well beyond Pier 6
- Camera inspection of three relief wells and drainage blanket collector conduit confirmed that a separation exists between the CMP roof and wood slat bottom of the “half moon”-shaped collector conduit
- Underlying pervious filter is compromised and is allowing foundation sand removal during high gradient flow

Several symptoms have led to the suggestion that the foundation is in distress, most likely related to voids beneath the stilling basin that have formed as a result of piping. A sinkhole appeared in the right overflow embankment in 1969 that may have been an early indicator of a future problem. A substantial increase in measured downstream movement of the dam noted over the last year has added to the dam owners' concern raised by discolored discharge waters observed during routine operation of the pressure-relief system.

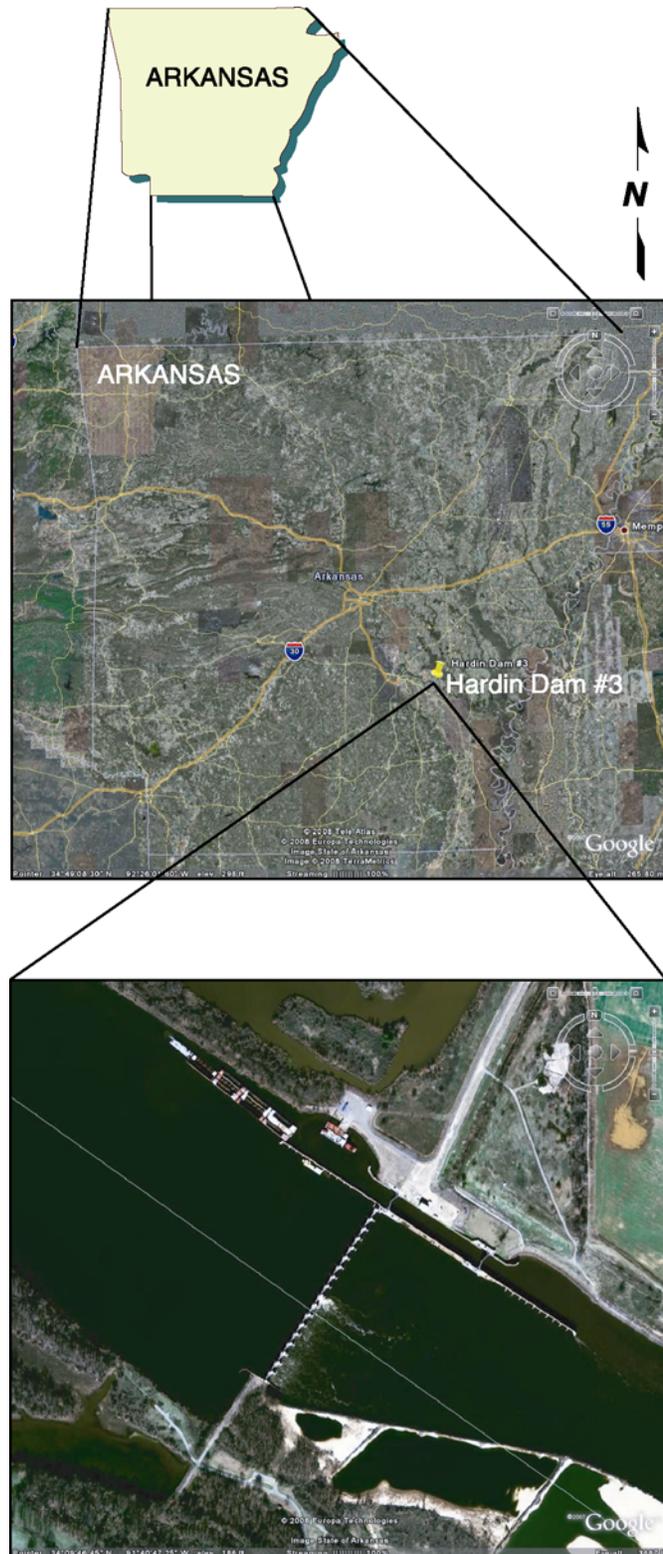


Figure 1. Hardin Dam #3 near Pine Bluff, Arkansas.

Accurately defining the areal and vertical extent of suspected voids is key to developing a mitigation plan that would reduce this structure's risk of failure. A geophysical technique using surface waves has proved highly effective on land in delineating analogous features. A few examples exist where MASW has been adapted to an underwater environment (Ivanov et al., 2000; Park et al., 2000; Park et al., 2005). Full wavefield recording with component separation and processing, followed by joint interpretation, was proposed to have the greatest potential for locating the culprit voids at sufficient resolution to pinpoint drill intersection through the reinforced concrete bottom of the stilling basin.

A cooperative effort between the Little Rock District of the U.S. Army Corps of Engineers and the Kansas Geological Survey (KGS) was undertaken in hopes of providing the highest quality MASW and first-arrival tomographic images possible around and through these voids. The MASW technique was invented at the KGS and the method has been used for a wide range of applications including two underwater surveys (North Atlantic on Grand Banks and Fraser River in British Columbia). Based on the suspected size and depth of the weakened subgrade, an imaging program was designed that centered around 24-channel hydrophone data using an underwater-shotgun source or slide-hammer impact source along a continuous profile across key areas of concern.

This project was designed to advance the methodology and provide a better understanding of energy partitioning and propagation at the surface and immediately below the surface of the stilling basin. These advancements and general observations had the potential to dramatically enhance the potential of the tool and provide a clear understanding of the potential of the method and areas in need of further research and development.

## **Characterization**

Geophysics used during site characterization routinely involves relatively noisy measurements of earth properties, qualitatively incorporated into working subsurface models with ground truth provided by observational data sets (e.g., drilling, outcrop studies, etc.). Evaluation of dam integrity and associated structures complicates and usually eliminates effective use of many geophysical tools due to structure geometries, conductive materials used during construction, utilities and operational workings, depth of investigations, and resolution requirements. Body-wave seismic techniques have not been extensively used due to survey costs and resolution requirements. With equipment improvements and technique developments and the wealth of information contained in the entire seismic wavefield (body waves and surface waves), seismic measurement or imaging data are routinely underutilized (Steeple et al., 1997).

This applied research project was designed to evaluate the applicability of several seismic techniques to identify and delineate abnormal physical characteristics or properties of materials beneath the stilling basin at Hardin Dam #3 near Pine Bluff, Arkansas, on the Arkansas River (Figure 1). Multichannel surface-wave inversion techniques have proved capable of detecting anomalous shear-wave velocity zones within and below a variety of surface materials (Miller et al., 1999). High-resolution seismic-reflection techniques routinely result in data that possess the potential for attribute analysis that can target zonations within the subgrade such as proposed beneath the concrete base of the stilling basin.

Surface waves are often used to deduce the  $V_s$  structure of soil and bedrock because of their ease in generation, propagation, separation, and processing (Miller et al., 1999; Stokoe et al., 1994). The propagation velocity (called phase velocity) of surface waves is frequency (or wavelength) dependent (this property is called dispersion). This dependency is determined

mainly by the vertical  $V_s$  variation. By recording surface waves of the fundamental-mode Rayleigh type propagating horizontally and directly from the seismic source, the dispersion property is measured and usually represented by a curve (called dispersion curve) depicting the variation of phase velocities with frequency. This curve is then used to back-calculate the vertical variation of  $V_s$  (called a 1-D  $V_s$  profile) through a process called inversion.

The multichannel analysis of surface waves (MASW) method (Park et al., 1999a; Xia et al., 1999; Miller et al., 1999) utilizes some of the pattern-recognition concepts provided by the multichannel recording and processing approaches. It employs multiple receivers (geophones) placed along a linear survey line with an equal spacing. Seismic waves generated by an impulsive source (like a sledgehammer) and propagating along the receiver line are recorded synchronously, enabling the recognition of various types of propagation characteristics.

Surface waves traditionally have been viewed as noise in multichannel seismic data collected to image targets for shallow engineering, environmental, and ground water purposes (Steeple and Miller, 1990). Recent advances in the use of surface waves for near-surface imaging have combined spectral-analysis techniques (SASW), developed for civil engineering applications (Nazarian et al., 1983), with multitrace reflection technologies exploited for near-surface investigations (Schepers, 1975) and petroleum applications (Glover, 1959). The combination of these two uniquely different approaches to seismic imaging of the shallow subsurface permits non-invasive estimation of shear-wave velocities (within 10% of measured) (Xia et al., 2002) and delineation of horizontal and vertical variations in near-surface material properties based on changes in these velocities (MASW) (Xia et al., 1999; Park et al., 1999a, 1999b).

Continuous acquisition of multichannel surface-wave data along linear transects has recently shown great promise in detecting shallow voids and tunnels (Park et al., 1999b; Miller et al., 2004a), mapping the bedrock surface (Xia et al., 1998; Miller et al., 1999), locating remnants of underground mines (Park et al., 1999a), and delineating fracture systems (Miller et al., 2001). Extending this technology from sporadic sampling to continuous imaging required incorporating MASW with concepts from the CDP (Mayne, 1962) method. Integrating these two methodologies resulted in the generation of a laterally continuous 2-D cross section of the shear-wave velocity field. Cross sections generated in this fashion contain information about the horizontal and vertical continuity and physical properties of materials as shallow as a few inches down to depths of over 300 ft in some settings.

The flexibility in acquisition and insensitivity to environmental noise allows successful use of shear-wave velocity profiling in areas where other geophysical methods might be limited. Surface waves, when used to image the earth, provide a rapid and relatively straightforward method of examining the shallow subsurface. Unfortunately, interpretations of the two-dimensional shear-wave velocity field derived from the inversion of the surface-wave dispersion curve are much lower resolution than seismic-reflection sections.

Surface-wave backscatter has been shown to be prominent in proximity to voids and/or abrupt horizontal discontinuities (Xia et al., 2003). Much like an echo of sound in a canyon or a wave bouncing off the shore of an otherwise calm pond, surface waves reflect/diffract after contact with an abrupt structural discontinuity such as a void or fault. Much of the tunnel detection success using seismic has come from reflected/diffracted surface waves (Miller et al., 2002; Miller et al., 2004b).

Emphasis of this research effort has been on surface waves as a principal wave type that would be sensitive to voids encountered and postulated at Hardin Dam #3. Three distinct components of the wavefield have proved effective providing information about tunnel structures in

border settings and across a range of near-surface settings (e.g., Otay Mesa, Tecate, and Chula Vista, all in California) by the investigators using an active-source seismic method (Miller et al., 2006). These three key wave types that have the greatest proven potential of sensitivity to void-like anomalies include surface waves, diffracted body waves, and refracted body waves. All these wave arrivals were thoroughly analyzed on the very limited number of shot records recorded at the Hardin Dam #3.

### Scholte Wave

In theory, surface waves may exist whenever a surface separates media with different elastic properties (Sheriff and Geldart, 1982). In terrestrial applications, measurements are made at the boundary (the “free” surface) separating air and solid earth. The term *surface waves* is commonly used as a synonym for the Rayleigh-type surface waves in recent applications. However, when measurements are made along the boundary where a body of water overlies solid materials, the behavior of surface waves changes slightly due to the interaction with the water (Stokoe et al., 1994). For the water-over-solid-earth case, they are called either Scholte waves or generalized Rayleigh waves, depending on whether the Rayleigh-wave velocity ( $V_R$ ) of the substrate layer (water-bottom layer) is smaller (soft substrate) or greater (hard substrate), respectively, than the P-wave velocity ( $V_w$ ) of water (Luke and Stokoe, 1998).

Analytical results indicate that the Scholte-wave velocity ( $V_{sch}$ ) and the generalized Rayleigh-wave velocity ( $V_{GR}$ ) are slightly different from the Rayleigh-wave velocity ( $V_R$ ) at the free surface and change with the surface-wave wavelength ( $\lambda$ ) to water depth ( $h$ ) ratio (Figure 2). Inversion of the Scholte-wave dispersion curve to a  $V_s$  profile requires a proper modeling scheme that accounts for the existence of the water layer above the measurement surface. However, considering that the maximum deviation of  $V_{sch}$  from  $V_R$  is usually less than 5 percent, that correction falls below the uncertainty level of the measurement. Treating the Scholte waves as identical to the Rayleigh waves during the inversion analysis does not appear to significantly degrade the confidence level of the calculated  $V_s$  profile for the soft-substrate case.

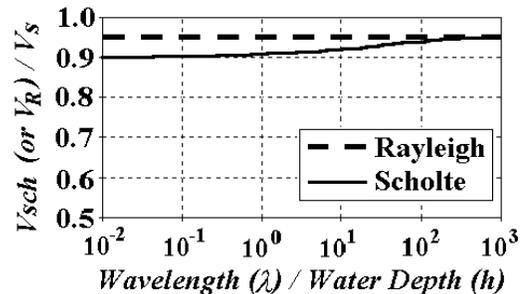


Figure 2. Approximate relationship between the Scholte-wave velocity ( $V_{sch}$ ) and the Rayleigh-wave velocity ( $V_R$ ) in comparison to the S-wave velocity ( $V_s$ ) (from Stokoe et al., 1994).

Adaptation of MASW to an underwater environment could be an innovative breakthrough in providing a quick, relatively inexpensive way to investigate shallow-water irregularities associated with dikes, levees, and dams. Structures designed for water retention and diversion are critical throughout the state of Kansas to both municipal water supplies and flood control. Development of MASW into a surveillance tool capable of detecting subtle changes in material rigidity or stiffness—especially as such stiffness would relate to voids—prior to the threat of failure could, at a minimum, reduce repair costs by focusing the efforts into problem areas. In the more extreme case, water-supply or flood emergencies resulting from leaks associated with structurally weak zones or—worse yet—material failure, could be preempted. The ultimate goal of developing underwater methodology is its application to structures through its use as a reconnaissance tool for investigating flanks and toes of levees, dikes, and dams and stilling basins and spillways of dams, eventually in an automatic mode.

### *Surface-Wave Diffractions*

A method has been developed at the KGS to detect near-surface tunnels (voids) directly from a shot gather based on a travelttime equation of Rayleigh-wave diffractions (Xia et al., 2003). Synthetic shot gathers were produced for several realistic models of voids in the subsurface. Diffracted surface waves were visible on the unprocessed synthetic shot gather (Figure 3). After Fk filtering was applied to suppress direct surface waves, the relative strength of diffractions increased significantly. The velocity of the diffracted wave was calculated to be the velocity of the direct surface wave, and the average depth to the void calculated to within 3% of the actual depth. This technique, applied to real data from a dissolution void in Ordovician-age limestone in the Metzgar Field in Easton, Pennsylvania, successfully detected the void and determined its actual depth to within 3 ft.

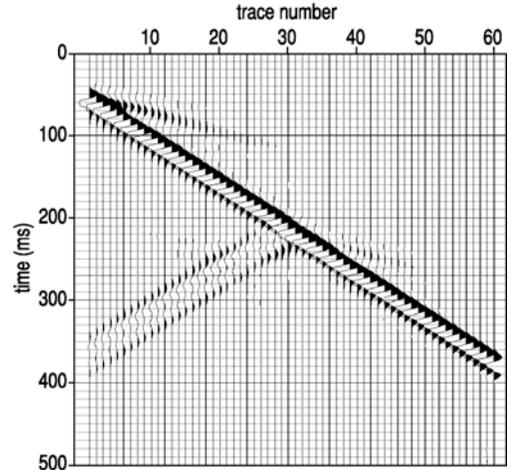


Figure 3. A synthetic shot gather of a 6 ft × 6 ft void at the depth of 6 ft in a homogeneous half space with the nearest offset of 3 ft and a trace interval of 3 ft.

### **DATA ACQUISITION**

Feasibility of detecting anomalous subbottom material in a shallow-water (>25 ft) setting was partially evaluated during this study. Based on the scientific literature, this investigation represents the first attempt to use a static water-bottom acquisition approach for collecting seismic data immediately downstream of a dam structure where potential anomalies immediately below the concrete apron at the bottom of a stilling basin were the principal target. Key to the success of this approach is the ability to place a static array of receivers along the bottom and record energy from a low-energy bottom-coupled seismic source. Although several of the critical conditions were not met, sampling of the wavefield with receivers placed at the bottom of the water column and top of the concrete slab provided the first and an extremely beneficial look at the full, shallow seismic wavefield in this environment.

High water flow through the south end of the dam resulted in unmanageable eddy currents behind gates on the north end that were closed to accommodate this investigation. The stilling basin behind Gate 1 (far north end of dam) was an essential area to study because of known sub-structure voids (Figure 4). Water depths varied through the day from over 20 ft in the morning to around 18 ft during acquisition of the 25 shot gathers. Variations in current velocity and gradient as well as water depths were a direct consequence of changes in stream flow throughout the day.

The source-and-receiver boat was outfitted to deploy the bottom-resting hydrophone cable and then provide a stable platform for the placement and detonation of the shotgun and impact water-bottom sources (Figure 5). With higher than expected river flows, currents became unmanageable and, with the addition of mechanical difficulties on the source/receiver boat, it became impractical to continue, thereby putting the equipment at risk. This continuous profile would have permitted investigation of both volumes of sub-slab sediments that were known to be stable and zones that were known to possess void space.



Figure 4. Gate 1 at the north end of Hardin Dam #3. Work boat pushed against outside wall of lock while preparing equipment for deployment. Current was strongly influenced by several open gates at the south end of the dam that were required open to pass the required spillway flow.

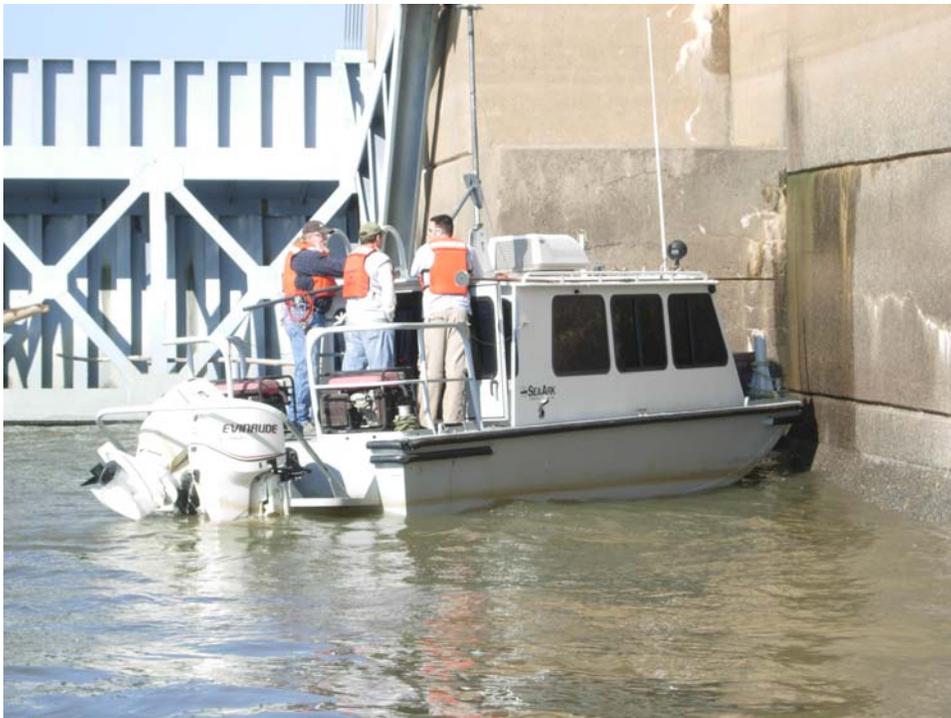


Figure 5. Source/receiver boat preparing to move along the downstream face of the dam, deploying the bottom-coupled hydrophone string. Water currents and the malfunction of one motor made stable operations from the work platform impossible with even the experienced boat crew assigned to the project.

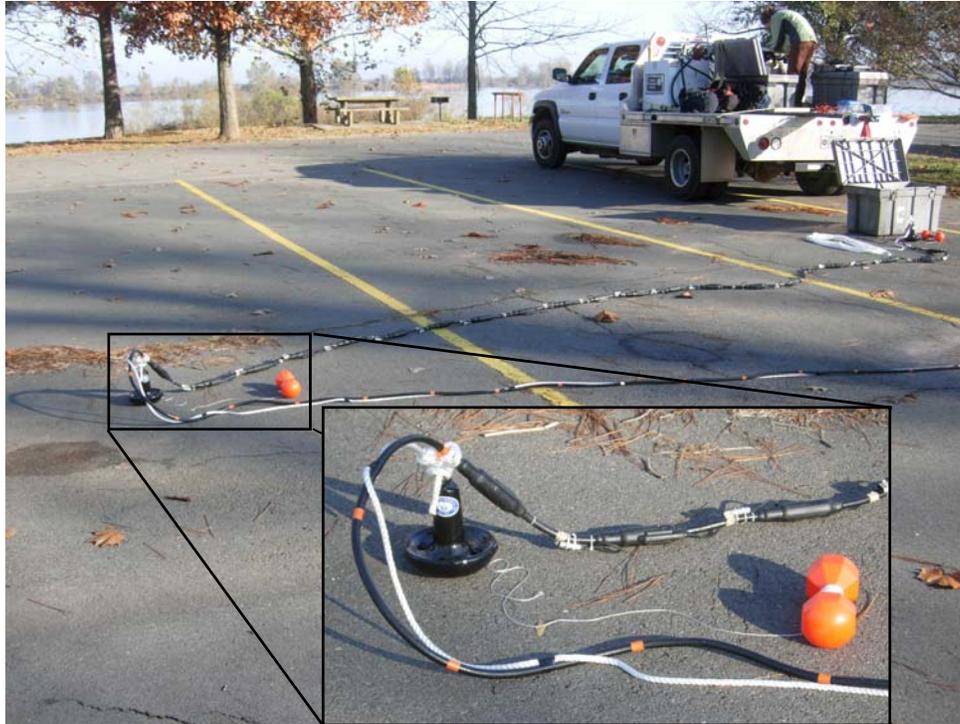


Figure 6. Hydrophone string with anchors on both ends and floats to allow location ties with the dam structure. Once on bottom, the hydrophone string would be dragged a fixed distance where it would lie static on the top of the stilling-basin slab to receive seismic energy from pre-determined source locations.

With the unknown condition at the surface of the stilling-basin concrete slab and the difficulty getting a confident and consistent contact between the concrete and receiver string, hydrophones were the sensors of choice for this study. The receiver string included 24 individual hydrophones, each separated by 1 ft (Figure 6). Placement of the receiving spread is critical to the planned analysis techniques and necessary for accurate and confident ties between the processed sections and the dam structure. To ensure the spread stayed stretched out and on the bottom, boat anchors were secured to both ends of the hydrophone stringer. Also, floats were attached to both ends of the spread to allow proper placement of the receiver line. Operationally, the spread would be anchored to the bottom at a specific location with the source placed an optimal distance off one end. Once the source was detonated and the resulting seismic energy recorded, the recording boat was to drag the spread a specified distance where another shot would be recorded. This sequence was planned to continue across the entire length of the dam to be investigated.

Strong and variable currents along the downstream face of the dam prohibited static deployment of the receiver spread and proved insurmountable for stable placement and detonation of the seismic sources (Figure 7). The source boat was not able to uniformly deploy the receiver spread and remain still enough to drop the source to the water bottom and detonate a shot. Swirling and variable water currents (eddies) were produced as a result of the large volume of water released at the south end of the dam while no water was released at the north end. This current environment could not be overcome by the two-work-boat configuration planned for this study. As a result, the two boats were lashed to the north pier of Gate 1 in a tail-to-nose configuration and were then used as a work platform. This allowed the boats to represent around 50 ft



Figure 7. Source/receiver boat deploying the receiver spread and attempting to maintain a stable platform for deploying and detonating the sources. Ideally the source/receiver boat would have the bow pointed south and centerline of the boat parallel to the dam axis.

of relatively secure platform on the downstream side for deployment and to hold the receiver spread. It also allowed movement along the spread to selected locations, providing various source-to-first-receiver offsets.

Once it became clear the continuous profiling approach would not be feasible under these river-flow conditions, the two boats were lashed together and to the containment (north) wall of the lock. Receivers were dropped to the bottom and secured to the boat siderail with rope. The two sources tested were both on 23- to 25-ft extensions, allowing above-water activation (Figure 8). The impact source was a steel shaft with a 6-inch-diameter steel plate on the bottom acting as a striker plate. Source timebreak was provided by a hammer switch secured to a 1-lb hammer used to deliver an impulsive energy impact to the top of the 23-ft steel shaft.

An explosive source was also used to produce seismic energy at the top of the concrete slab. For safety, a 12-gauge black-powder blank shotgun shell was attached to the bottom of the screw-jointed, 25-ft-long PVC pipe and lowered to the water bottom without a firing mechanism (Figure 9). The lowering of the charge to the bottom was accomplished by adding joints of PVC (Figure 10). Once securely placed at the water bottom, a steel plug with a firing pin was dropped from the surface through the PVC, with detonation occurring once the weighted firing pin pierced the shell casing (Figure 11). If for any reason the PVC and bottom-secured shell were to get loose, a steel safety cable was available to pull the source back to the boat's work deck.



Figure 8. Transported to the test site on the cabin of the work boat were two pole-mounted sources. One was an impact source using a hammer to strike the top of a 23-ft-long steel shaft connected to a 6-inch-diameter striker plate. The second source was a 12-gauge shotgun shell attached to the bottom of a 25-ft-long PVC pipe with a velocity sensitive timebreak.



Figure 9. Explosive-source shell holder with red 12-gauge black-powder shell being inserted into the steel sleeve. The sleeve is then screwed into the pipe, making it ready to lower to the water bottom and drop the firing pin into.



Figure 10. Mating the segments of the underwater blank and shotgun-shell seismic source. Orange cable is for timebreak and steel cable is for safety in case firing rod is dropped.



Figure 11. Weighted firing pin being dropped 25 ft to impact 12-gauge blank shotgun shell firmly pressing on top of concrete apron at the bottom of the stilling basin near Gate 1.

A total of 25 shot records were acquired from eight different source locations and two different spread placements along the northern half of Gate 1. Data from the explosive source (12-gauge black-powder blank shotgun shell) can be characterized as possessing an extremely high amplitude pressure wave consistent with the well-known characteristics of a water column. The amplitude of the first arrivals was so large the data are clipped (amplitudes exceeded the seismograph's recording limit). Shot gathers from the impact source (1-lb hammer against top of steel shaft) are much lower energy and possess interpretable surface waves (Figure 12). Considering the velocity contrast between a water-filled void and water-saturated sediments, there is no hope of observing changes in body energy related to the expected voids. However, considering the strong dependence of surface waves on the shear-wave characteristics of the media, anomalous surface-wave arrivals should be the overwhelming wave of choice when looking for voids in this setting.

Evident on both gathers presented in this report are arrival patterns that appear characteristic of voids as modeled and observed at several sites with culverts, tunnels, and fault/fractures on land seismic data. This curved arrival, interpreted on shot gathers to possess an apex at around receiver 15 or approximately 10 stations from the source, is consistent with a diffraction with a phase velocity consistent with an 8- to 10-ft depth of penetration (or imaging depth). The anomalous curved arrival appears to be originating from a location about 8 to 10 ft below the top of the concrete slab and directly beneath the hydrophone spread. This would equate to a spot about 35 ft from the south side of the lock wall, which is also the northern extreme of the downstream dam structure (north edge of Gate 1). This curved seismic return could be from any one of several types of anomalous features (anomalous to a normal layered earth). Included on that

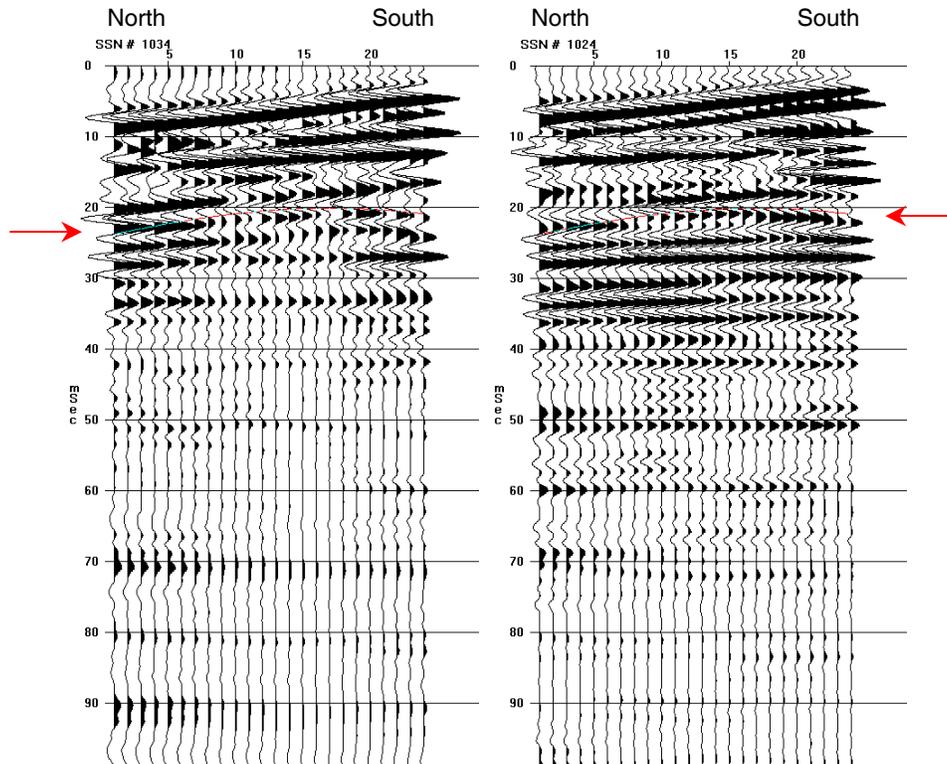


Figure 12. Shot gathers from the hammer source with a red curved (hyperbola) line marking the top of the interpreted anomalous reflected/diffracted surface wave.

list are man-made foundation structures, voids, out-of-the-plane scatterers, boulders, construction fill, etc. The seismic return is, however, similar to model representations of what voids/tunnels look like.

## **Conclusions**

Seismic detection of voids beneath submerged portions of dam structures like the voids suggested to be intermittently present under the stilling basins below Gates 1 through about 6 at Hardin Dam #3 on the Arkansas River is possible. This suggestion is based on the test data recorded during a modified feasibility study with a geophysical survey centered at the northern half of the Gate 1 stilling basin, and which showed certain data patterns that could be suggestive, though not conclusive, of voiding that is known to be present at that location. The lateral extent of the survey line was planned to include sampling of the stilling basin segment that is known to have voids, and also segments suspected to be void free, thus providing results for comparison and refinement of data interpretation. This was not possible, however, due to the limited extent of the survey as a result of high river flow being passed on the far south end of the dam (right abutment) and the resulting turbulence caused in the area of the survey at the left abutment.

Seismic sources and a unique receiver deployment proved effective and resulted in data that allowed key wavefield characteristics to be evaluated, allowing improvements in acquisition philosophies that will increase the likelihood of success on any future attempt to use seismic as a void-detection approach. Key is direct contact with the concrete pad, low energy impact, broad coupling area, and careful attention to source-receiver offsets. Working from a fixed platform would be optimal and very rapid. Employing work boats is a low-cost option that would require minimal river flow and skilled boat crews.

Body-wave energy arrivals are, for the most part, all from within the water column. Direct waves, air/water multiples, out-of-the-plane reflections from the dam structure, etc., are all present and represent noise when the target is below the concrete pad. Body waves are high frequency, with notably broad bandwidths and therefore a near-impulsive minimum-phase wavelet.

Surface waves are markedly lower frequency and propagate at a lower velocity than the water wave, making them distinctive. Disturbances in the lateral propagation of the survey wave are not evident, but scatter, diffraction, or reflections associated with anomalous sub-structure material appear to be evident. The arrival characteristics (pattern (x-t), apex arrival time, apparent velocity, frequency, etc.) are all consistent with seismic models that have been produced for a variety of tunnels, voids, fractures, and faults that interrupt the otherwise laterally consistent earth.

This test, although not successful in delineating the extent and location of the void areas, did provide extremely encouraging results with respect to the potential of this tool if the site logistics and equipment can be optimized for the seismic-energy propagation characteristics as observed on these data. An improved platform would dramatically increase the potential for continuous and redundant imaging. Reduced source energy, broader energy transfer area, and decreased source frequency would improve the potential of the recorded surface waves to be processed to enhance the target voids at this site.

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