ERDC/GSL TR-09-16

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Infrasound Assessment of Infrastructure

Report 6: Scour Detection and Riverine Health Assessment Using Infrasound

R. Danielle Whitlow, Oliver-Denzil S. Taylor,
Mihan H. McKenna, and Meghan C. L. Quinn

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Report 6 of a series

Prepared for Headquarters, U.S. Army Corps of Engineers
Washington, DC 20314-1000

Abstract

A previously initiated proof of concept study using infrasound to detect changes in the vibrational modes of a bridge caused by scour was extended to include three-dimensional (3-D) models of a shallow foundation case and of a deep foundation case. Comparisons were made between the two-dimensional (2-D) and 3-D cases of the shallow foundation, and the results showed that plane-strain conditions represent the lowest frequency fundamental modal changes. As such, a 2-D model of the bridge substructure can be used to realistically simulate progressive scour conditions while reducing the overall computational requirement. Results from the analysis of the deep foundation case proved the potential of the use of infrasound for scour detection for pile foundations. Also included are investigations into the correspondence of the critical depth seen in plots for deep foundations with pile buckling capacity and riverine health assessment using infrasound.

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Preface

This investigation was sponsored by the Denied-Area Monitoring Using Infrasound (DAMUI) project under the Center Directed Research Initiative (CDRI) and Military Engineering 6.2 Remote Assessment of Critical Infrastructure (RACI) program. This report was prepared by R. Danielle Whitlow, Dr. Oliver-Denzil S. Taylor, and Dr. Mihan H. McKenna of the Structural Engineering Branch (StEB), Geosciences and Structures Division (GSD), Geotechnical and Structures Laboratory (GSL), U.S. Army Engineer Research and Development Center (ERDC) and Meghan C.L. Quinn of the New England District, U.S. Army Corps of Engineers.

During this investigation, Chuck Ertle was Chief, StEB; Dr. Amy Bednar was Acting Chief, GSD; Dr. William P. Grogan was Deputy Director, GSL; and Bartley P. Durst was Director, GSL.

COL Brian S. Green was Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic inches	1.6387064 E-05	cubic meters
feet	0.3048	meters
inches	0.0254	meters
inch-pounds (force)	0.1129848	newton meters
pounds (force) per inch	175.1268	newtons per meter
pounds (force) per square inch	6.894757	kilopascals
square inches	6.4516 E-04	square meters
square yards	0.8361274	square meters

1 Introduction

Scour is a commonly encountered issue for both military operations and civil works. All bridges within the U.S. National Bridge Inventory must be inspected every 2 years as required by law. As part of this inspection, the bridge substructure and channel are inspected. Routine inspection of underwater portions of the substructure is limited to times of low flow and is accomplished either by visual means or by wading. If water is more than waist deep, specially trained divers must be used to conduct the underwater inspection of the substructure. These underwater inspections are required to occur on 48-month cycles. For bridges deemed to be scour critical, defined by the National Bridge Inventory Standards as having “a foundation element that has been determined to be unstable for the observed or evaluated scour condition,” additional monitoring most commonly including additional inspections beyond law requirements, portable monitoring systems, and/or fixed monitoring systems with visual inspections may be specified. As of 2011, the number of scour critical bridges increased from approximately 20,900 in 2009, to just over 25,000 in 2011. This increase was due in part to changes concerning how bridges with unknown foundations were assessed.

In 2011, approximately 42,200 bridges were classified as having unknown foundations meaning that no plans, either design or as-built, existed for the structure. Initially, bridges classified as having unknown foundations were exempt from the required complete scour analysis to determine scour hazard because of the lack of procedures or guidance for bridge owners to determine the foundation characteristics required for a scour evaluation. The Federal Highway Administration (FHWA) released a series of memorandums in 2008 and 2009 containing new guidelines aimed at reducing the number of bridges classified as having an unknown foundation (Lwin 2009a and 2009b; Gee, 2008). These guidelines indicated that all bridges coded as having an unknown foundation should be re-evaluated through the use of either nondestructive testing or risk assessment to attempt to identify foundation type so that a scour analysis could be completed. Barring this, the new guidelines indicated that bridges still coded as having an unknown foundation must have a plan of action (POA) in place similar to the one required for scour-critical bridges. This POA typically consists of additional monitoring using either portable or fixed monitoring systems.

Current monitoring systems are not truly remote systems in the sense that they must be installed on or near the bridge, such as around bridge piers or abutments in the channel bed or on the piers and abutments themselves. Monitoring systems, both fixed and portable, are subject to damage from a variety of factors including high flows, debris, severe water temperatures, and vandalism that reduce the effectiveness of monitoring the health of the structure (Lee et al. 2012; Hunt 2009). Further, a monitoring system was required for each structure, which is a substantial cost for owners of multiple bridges. Therefore, the purpose of this research is to investigate the use of infrasound as a truly remote monitoring system to detect and assess scour hazards.

Infrasound is a low-frequency, sub-audible sound, that is typically accepted to be within the 0.1- to 20-Hz range. Due to the long wavelengths of infrasound, little attenuation of source characteristics occurs even at considerable distance, from tens to hundreds and even thousands of kilometers depending on source strengths. This allows for omni-directional, persistent monitoring of large areas with a minimal investment in hardware. There are many natural sources of infrasound including avalanches, meteors, severe weather systems, tornadoes, turbulence, earthquakes and volcanoes (Bedard and Georges 2000; Evers and Haak 2010). In addition to these natural infrasound sources, large infrastructure such as bridges, dams, or large buildings, also generate infrasound at either their own natural or driven frequencies (McKenna et al. 2009a and 2009b; Kobayashi 1999; Donn et al. 1974).

The technical report series, ERDC/GSL-09-16 *Infrasound assessment of infrastructure*, details the research efforts to determine whether low-frequency sound (infrasound) can be used to monitor structures at a distance to satisfy force projection remote assessment of infrastructure needs. The determination of the structural capacity of the selected test bridge is presented in Report 1: *Field testing and finite element analysis for a railroad bridge, Ft. Leonard Wood, Missouri* (Diaz-Alvarez et al. 2009). Report 2: *Experimental infrasound measurements of Railroad Bridge A.B 0.3, Ft. Leonard Wood, MO* (McKenna et al. 2009c), and Report 3: *Numerical simulation of structural-acoustic coupling and infrasonic propagation modeling for Railroad Bridge A.B. 0.3, Fort*

Leonard Wood, Missouri (McKenna et al. 2009a) describe (1) the geophysical data collection and the processing of the infrasound data with concurrently developed continuous-wave techniques and (2) the acoustical modeling performed on the target bridge to assess the coupling of the structure to the surrounding medium, air, and (3) the propagating of this energy out to tactical distances. A representational infrasound source based on the bridge's geometry and material characteristics was developed in conjunction with the assessment of the effects of local topography on far-field propagation.

Report 4: *Investigation of scour detection using infrasound for Railroad Bridge A.B. 03, Fort Leonard Wood, Missouri* (Whitlow et al. 2012) documented the current state of practice for scour monitoring for both civil works and military operations as well as presented a proof-of-concept study using infrasound to detect a scour condition at a bridge based on the changing resonance of the structure caused by altering the boundary conditions of the structure (i.e., removal of overburden as scour deepens) using the railroad truss at Ft. Leonard Wood previously studied in the technical report series. Report 5: *Vibration and acoustic analysis of Railroad Bridge A.B. 03, Fort Leonard Wood, Missouri* (Costley et al. 2012) investigated the response of the Ft. Leonard Wood railroad truss to vehicle excitation both as a potential means of remotely monitoring a structure for capacity and number of vehicles traversing the bridge and as a method for monitoring for significant damage.

This report extends the proof of concept study using infrasound to detect a scour condition at a bridge based on the changing resonance of the structure as caused by altering the boundary conditions of the structure (i.e., removal of overburden as scour deepens) for both the shallow foundation case and the deep foundation case. This report also investigated two anomalies relating to riverine health assessment.

Reports 1 through 5 of this series focused on a steel, through truss railroad bridge with spread footings over the Little Piney River in Ft. Leonard Wood, MO. Report 4 of this series investigated the use of infrasound for scour detection at shallow foundations, focusing on this same bridge. The study provided a proof-of-concept designed to show that scour detection around bridge piers or at abutments was possible using the change in the vibrational modes of the bridge caused by scour, detectable as infrasound. Results for the two-dimensional (2-D) plane strain case were promising and showed that the use of infrasound to detect scour at bridge piers was a possibility. This report expands the study to include:

- Investigation of the shallow foundation case as a three-dimensional (3-D) model coupled with the structural superstructure model of the Little Piney River railroad truss.
- Comparison of the results of the 2-D and 3-D shallow foundation models.
- Investigation of a bridge pier on the Louisiana side of the Interstate 20 (I-20_{LA}) bridge over the Mississippi River in Vicksburg, MS, as a deep foundation case to determine if scour was detectable with other typical foundation types.

2 Model Development and Analyses

As with previous reports in this series, COMSOL™ Multiphysics Finite Element modeling was used to determine the change in bridge pier behavior due to changes in lateral earth pressure, or scour, for both 2-D and 3-D cases for shallow foundations and for the 2-D case for deep foundations using the structural and acoustic modules. Both the shallow and deep foundation cases were tested with two soil types: dense sand and silt. Based on data obtained from a soil map of the Ft. Leonard Wood area published by the U.S. Department of Agriculture and National Resources Conservation Service (Larsen 2002) and other reported soil site conditions, the parameters shown in Table 1 were determined and input into COMSOL as soil properties. Two soil types were tested in the model, the generalized properties of which are shown in Table 1.

Table 1. Soil parameters entered into COMSOL.

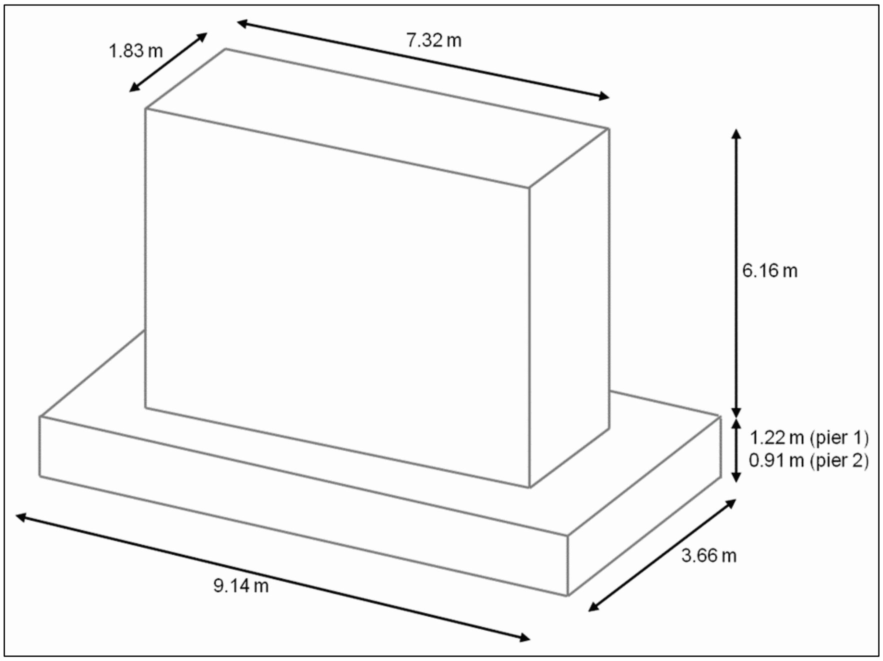
Property	Sand	Silt
Density (kg/m^3)	1800	1600
Poisson's Ratio	0.4	0.3
Young's Modulus (Pa)	80e^6	65e^6
P-wave (m/s)	750	450
S-wave (m/s)	450	220
Cohesion (Pa)	0	5e^3
Angle of Internal Friction	38°	30°

For each of these soil types, the degree of scour was varied from a zero scour condition to a total scour condition, and a frequency analysis was performed at each interval.

Little Piney River railroad truss at Ft. Leonard Wood, MO

Figure 1 shows a schematic of the concrete spread footing for the Little Piney River railroad truss at Ft. Leonard Wood, MO. This model is based on plans obtained from the Ft. Leonard Wood Directorate of Public Works.

Figure 1. Little Piney River railroad bridge pier schematic.



Dead and live loads representing the bridge superstructure and a single train engine, respectively, were applied where the superstructure contacted the top of the pier. The train engine was used as an excitation source in the original study and applied to our models for comparative analysis. Earth pressures representing the soil-water media were applied along the vertical faces of the spread footing as a user-defined boundary condition. To simplify soil-structure interaction, a spring boundary condition similar to the Winkler model (Dutta and Rana 2002; Winkler 1867) was applied to the bottom of the footing, representing the compressibility of the foundation soil.

The degree of scour was modeled as a variation in lateral pressure from a reduction of soil in increments from the elevation of initial overburden to the total scour condition. At each of these elevations, a frequency analysis was conducted and the eigenfrequencies of up to 230 modes were calculated. Only modes below 20 Hz, the upper limit of the infrasound passband, were considered. For each mode in this range, the variation in eigenfrequency with degree of scour was plotted to determine both the overall frequency variation and the correlation of this variation with scour depth. For infrasound to be a viable tool in remote scour detection and assessment, a detectable frequency, significant variation, and a strong correlation with depth of scour must be prevalent. Here, a significant variation is defined as one exceeding 0.2 Hz, and preferably higher. This variation is readily detectable using current infrasound sensors and signal processing techniques, which can provide a detectable resolution of 0.05 Hz.

Two-dimensional case

For the 2-D case, the soil was reduced in 0.5-m increments from an initial overburden dependent on soil type (i.e., 1.0-m for dense sand and 2.0-m increment for silt) to a total scour condition corresponding to the bottom of the footing. A frequency analysis was performed at each of these elevations. The eigenfrequency, f, and the fundamental eigenvalue, λ, were solved through Equations 1 to 4.

$$-\rho\omega^2\boldsymbol{u}-\nabla\sigma=F_v \tag{1}$$

where the normal stress, $(\sigma \cdot \boldsymbol{n})$, is defined as

$$\sigma\cdot\boldsymbol{n}=-\boldsymbol{k}_A\left(\boldsymbol{u}-\boldsymbol{u}_o\right)\left(1+j\eta_k\right)-\boldsymbol{d}_A j\omega\boldsymbol{u} \tag{2}$$

$$i\omega=\lambda \tag{3}$$

$$-\lambda/2\pi i=f \tag{4}$$

where ρ is the density, ω is the angular frequency, $\boldsymbol{u}$ is the displacement, $\boldsymbol{k}_A$ is the spring constant vector, η_k is the damping loss factor vector, $\boldsymbol{d}_A$ is the viscous damping vector, and F_v is the force vector. The values for the spring constant and damping loss factor were determined from a static analysis in which a deflection of no more than 2 cm was calculated based on the modeled train engine loads from Diaz-Alvarez (2009) and Costley et al.(2011).

Three-dimensional case

For the 3-D case, the increments described above were used. The eigenfrequency, f, and the fundamental eigenvalue, λ, were solved through Equations 5 to 11

$$-\rho\omega^2\boldsymbol{u}-\nabla\sigma=F_v \tag{5}$$

where the normal vertical stress, $(\sigma \cdot \boldsymbol{n})$, is defined as

$$\sigma \cdot \boldsymbol{n} = -\boldsymbol{k}_A (\boldsymbol{u} - \boldsymbol{u}_o)(1 + j\eta_k) - \boldsymbol{d}_A j\omega \boldsymbol{u} \tag{6}$$

where the normal lateral resistance $(\sigma \cdot \boldsymbol{n})_S$, is defined as

$$(\sigma \cdot \boldsymbol{n})_s = \frac{F_{tot}}{A}(1 + j\eta_k) - \boldsymbol{d}_A j\omega \boldsymbol{u} \tag{7}$$

where F_{tot} is the total spring boundary force as a function of extension

$$F_{tot} = F_{tot}(\boldsymbol{u}_{spring}) \tag{8}$$

$$\boldsymbol{u}_{spring} = (\boldsymbol{u} - \boldsymbol{u}_o) \tag{9}$$

Thus, the eigenfrequency is solved

$$i\omega = \lambda \tag{10}$$

$$-\lambda / 2\pi i = f \tag{11}$$

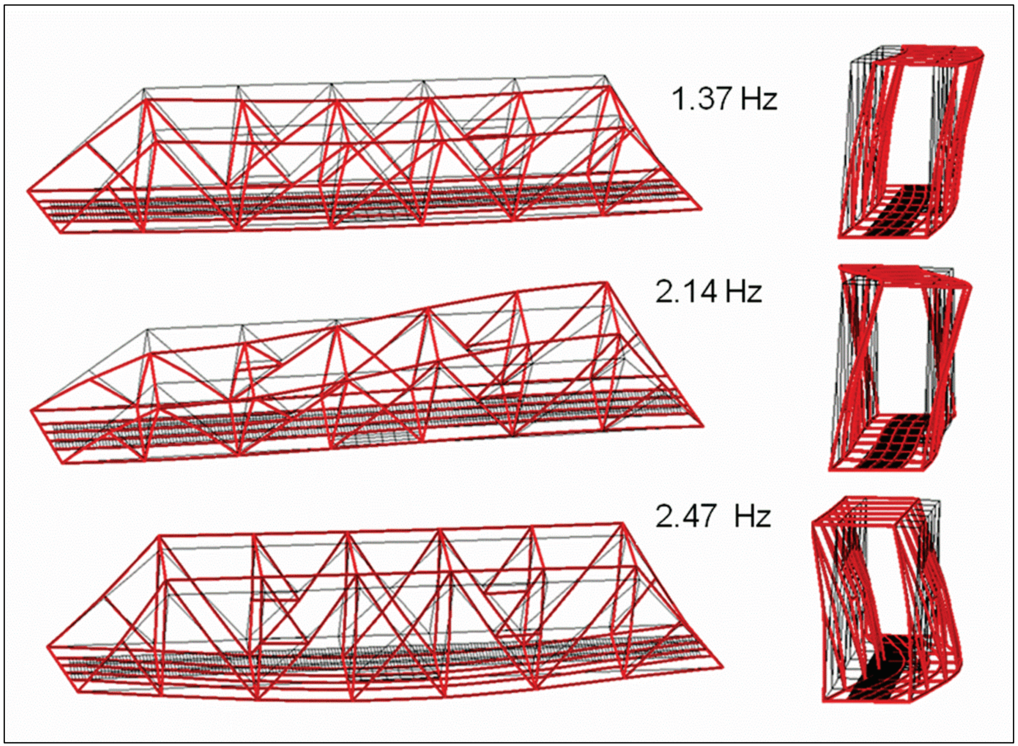
where ρ is the density, ω is the angular frequency, $\boldsymbol{u}$ is the displacement, $\boldsymbol{k}_A$ is the spring constant vector, η_k is the damping loss factor vector, $\boldsymbol{d}_A$ is the viscous damping vector, and F_v is the force vector. The values for the spring constant and damping loss factor were determined as described for the 2-D case.

Again, the degree of scour was modeled as a variation in lateral pressure as a reduction of soil in increments from the elevation of initial overburden to the total scour condition. For the 3-D case, this variation occurred on only two sides of the model. As determined by soundings from inspection reports for the bridge, these were the only locations of scour for the pier.

Comparison of 2-D and 3-D cases

Costley et al. (2012) refined previous Ft. Leonard Wood 3-D finite element superstructure models (Costley et al. 2011; Diaz-Alvarez et al. 2009) to assess the modal displacements for vehicular traffic at low infrasonic frequencies. The results (Figure 2) illustrate minor translational modal deformations within the 1- to 3-Hz passband with no significant impact on the piers.

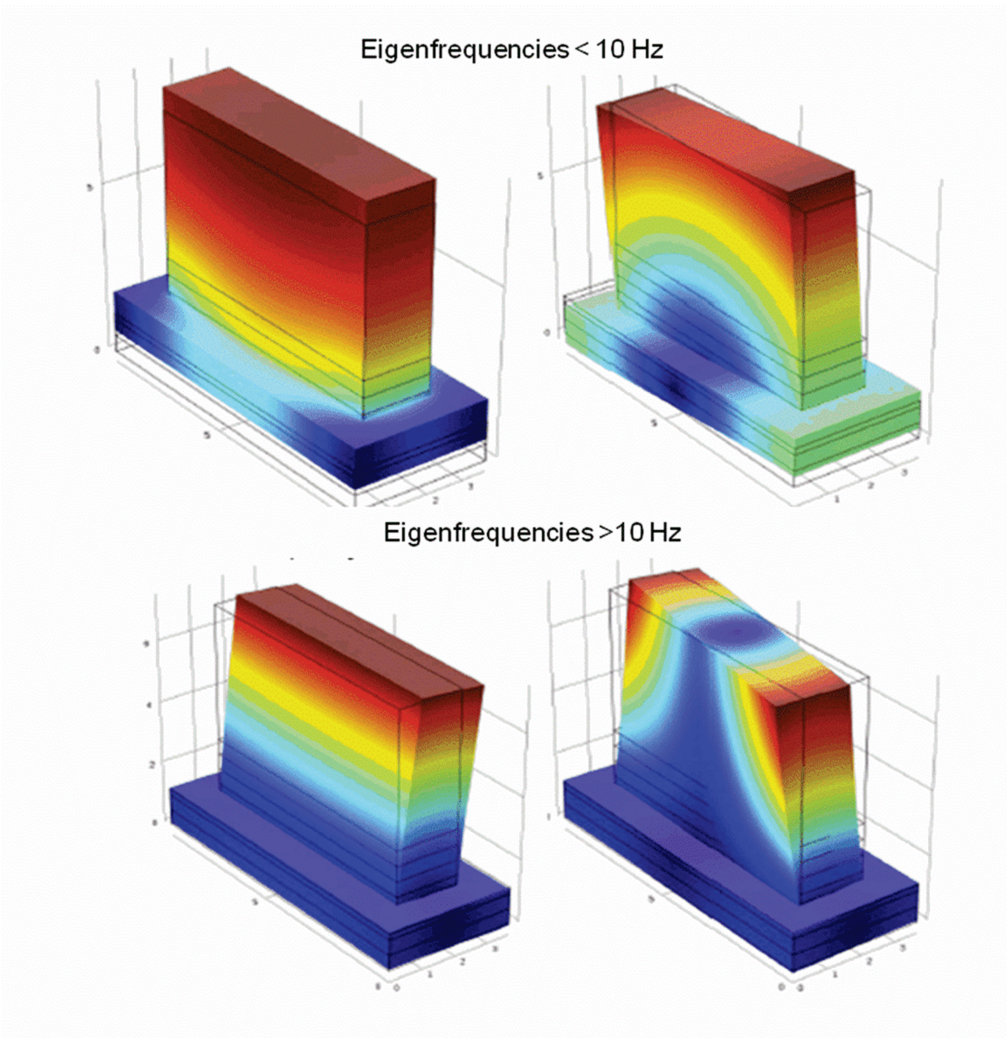
Figure 2. Superstructure eigenmode deformations within the 1- to 3-Hz passband for Ft. Leonard Wood bridge (from Costley et al. 2012)



However, the 3-D pier models in Figure 3 indicate that the lower modal frequencies significantly affect the foundation base and the pier's vertical and translational deformations. In the figure, blue represents an area of little deformation while red indicates an area of high deformation.

Higher modal frequencies, corresponding to the longitudinal and torsional deformations, do not have a significant impact on the foundation base loading; however, the deformation of the piers due to scour could have an additive effect on the deformation of the superstructure. As the loss of stiffness in the substructure was determined through the change in lateral earth pressures representing the removal of material through scour, it can be concluded that scour of the base material will significantly affect the lower frequencies and have minimal, if any, effect on the higher modes. Additionally, the 3-D deformations of the superstructure and substructure eigenmodes (Figures 2 and 3, respectively) indicate that 2-D plane-strain modeling can adequately model changes in resonant frequencies for vertical and translational failure modes (i.e., the lowest modal frequencies that are most representative of loss of structural stiffness due to decreased earth pressures). As scour increases, the transverse stiffness decreases more significantly than the longitudinal stiffness due to the coupling of the superstructure. Thus for these models, plane-strain conditions represent the lowest frequency fundamental modal changes. As such, a 2-D model of the bridge substructure can be used to realistically simulate progressive scour conditions while reducing the overall computational requirement. Additionally, these lower frequencies are most readily detectable through infrasound.

Figure 3. Eigenfrequencies observed with an earth pressure equivalent to 3 m of silt.



Interstate 20 (I-20$_{LA}$) Bridge over the Mississippi River in Vicksburg, MS

A permanent infrasound array was emplaced in Vicksburg, MS to facilitate continuous monitoring of both an old railroad truss and the Interstate 20 (I-20$_{LA}$) Bridge over the Mississippi River in Vicksburg. The Denied Area Monitoring and Exploitation of Structures (DAMES) Array is a seismic-acoustic array installed at the U.S. Army Engineer Research and Development Center (ERDC) Waterways Experiment Station site in Vicksburg, MS. The DAMES array has a nested five-element 60-m tactical array at the IML1/Hub site, identical to the deployed and operational experimental arrays operated by ERDC, as well as a four-element array with maximum aperture of 1.8-km, designed to be comparable to the nuclear Comprehensive Test Ban Treaty Organization (CTBTO) International Monitoring System (IMS) arrays for sub-hertz signals. Each location includes an Intermountain Laboratory (IML) Model ST infrasound gauge, a Chaparral Model 24 infrasound gauge, a B&K Model 4952 A audible acoustic microphone, and a Geospace GS-1 3C SeisMonitor 1-Hz seismometer. The infrasound gauges are all equipped with four 50-ft porous hoses to reduce wind noise contamination of the signals of interest. Data from the DAMES array are continually recorded on Reftek 130-A digitizers at 1,000 samples per second and archived onsite at the ERDC. Figures 4 and 5 show the 60-m DAMES tactical HUB array layout and the 1.8-km cross layout, respectively.

These arrays provided the opportunity to study an additional foundation type, a deep foundation, after the initial study concerning the use of infrasound for scour detection showed validity. Figure 6 shows a schematic of a bridge pier on the Louisiana side of the Interstate 20 (I-20_{LA}) Bridge over the Mississippi River in Vicksburg, MS. The model is based on as-built drawings of the bridge. The initial model for the deep foundation case was a 2-D, simplified model of the pier, shown as the shaded portion of the schematic in Figure 6.

As with the spread footing of the Little Piney River railroad bridge, the degree of scour for the deep foundation case was modeled as a variation in lateral pressure as a reduction of soil in increments from the elevation of initial overburden to the total scour condition. Initial overburden for the deep foundation case was set at 1 m above the footing, representing the zero scour condition, and was varied incrementally to the following scour depths: top of footing, middepth of footing, bottom of footing, and at 1, 2, 3, and 6 m of exposed piles.

At each of these elevations, a frequency analysis was conducted and the eigenfrequencies of 230 modes were calculated. Only modes below 20-Hz, the upper limit of the infrasound passband, were considered. For each mode in the appropriate range, the variation in eigenfrequency with degree of scour was plotted to determine both the overall frequency variation and the correlation of this variation with scour depth. For infrasound to be a viable tool in remote scour detection and assessment, a detectable frequency, a significant variation, and a strong correlation with depth of scour must be prevalent. Here, a significant variation is defined as one exceeding 0.2 Hz, and preferably higher. This variation is readily detectable using current infrasound sensors and signal processing techniques, which can provide a detectable resolution of 0.05 Hz.

Figure 4. DAMES tactical HUB array layout.

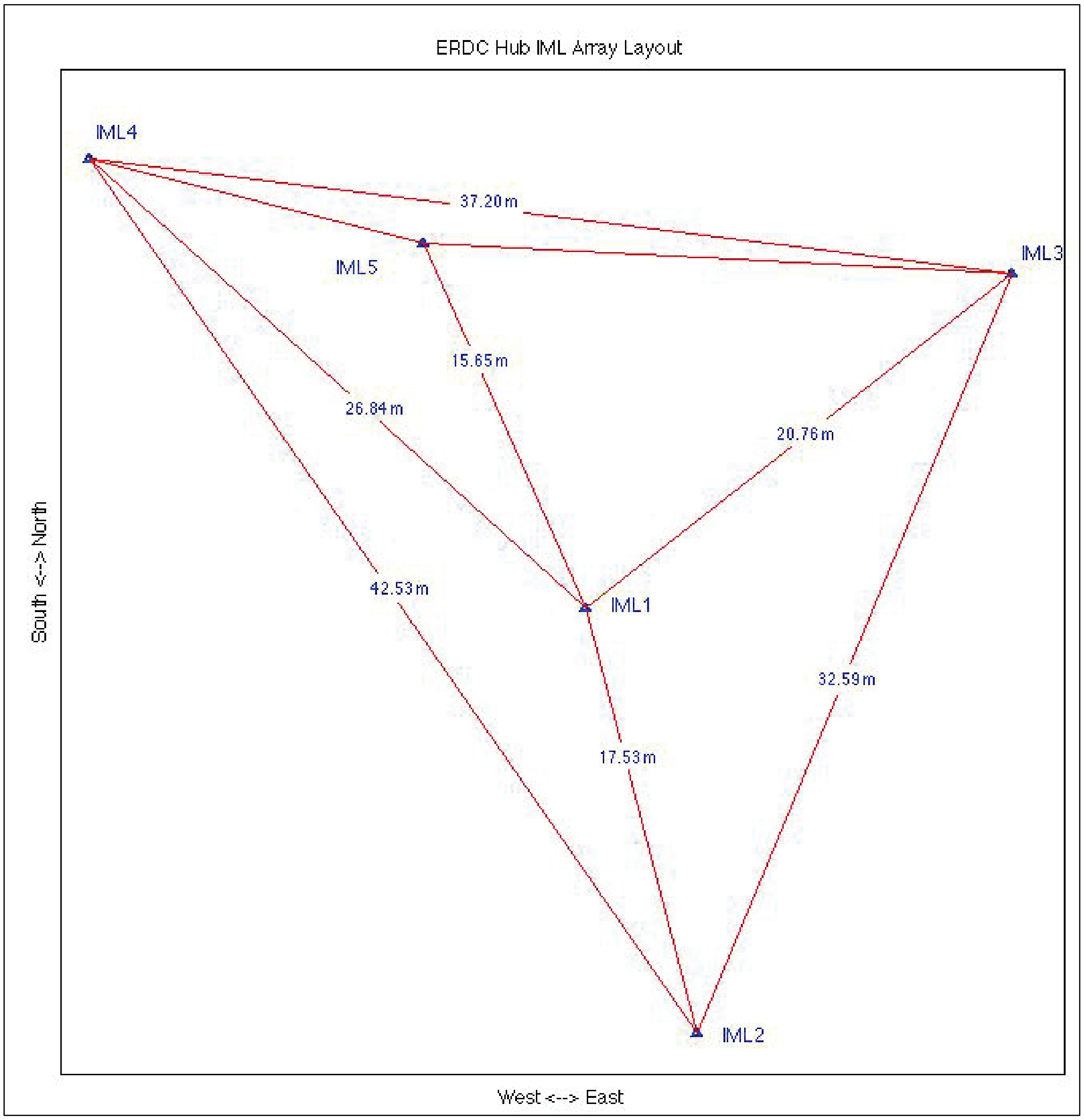


Figure 5. DAMES 1.8-km array layout.

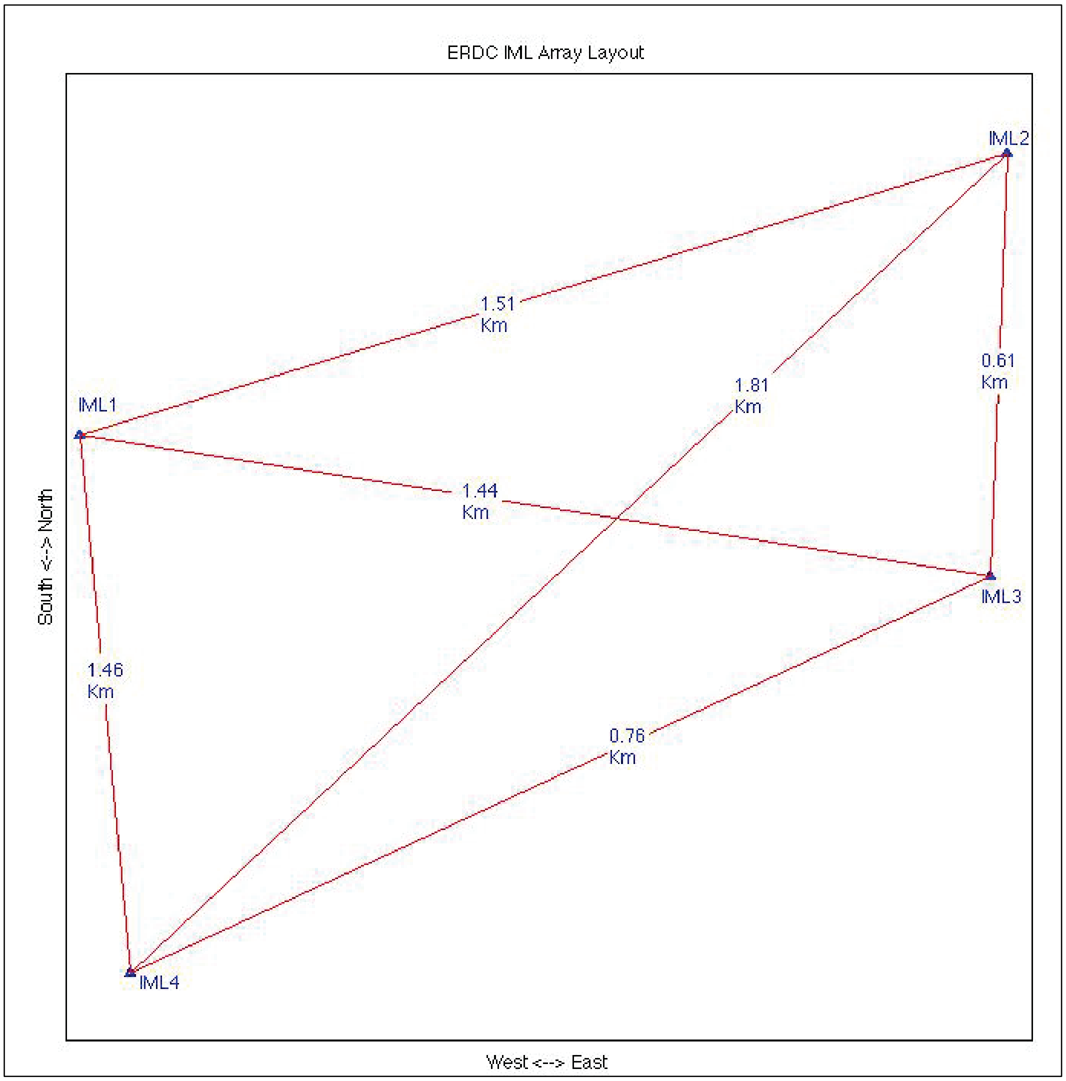
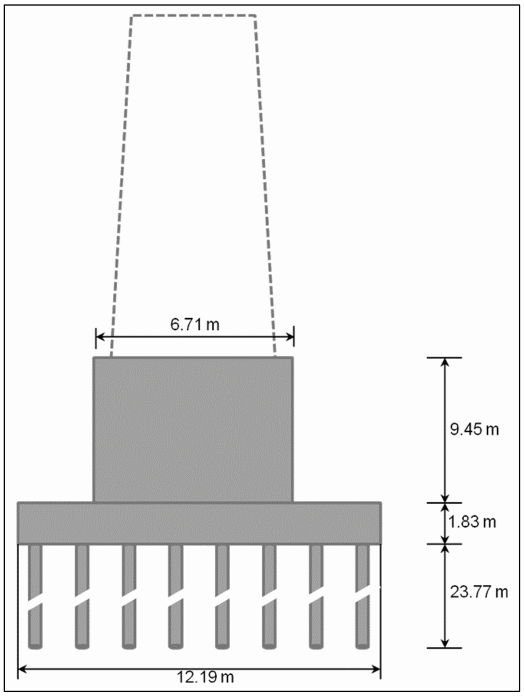


Figure 6. Interstate 20 ($I\text{-}20_{LA}$) Bridge (Vicksburg, MS) pier schematics



3 Results

Little Piney River railroad truss at Ft. Leonard Wood, MO

With the increase of scour depth by the prescribed interval, the eigenfrequencies from the frequency analyses were studied to detect the frequency difference in each mode within the infrasound passband. For the two soil types tested, the highest degrees of variability were at 2.65 Hz, 5.5 Hz, 7.66 Hz, 11.09 Hz, and 13.51 Hz for dense sand and 2.40 Hz, 4.33 Hz, 6.02 Hz, and 12.40 Hz for silt.

To establish a correlation to scour hazard potential, the changes in frequency were then plotted against scour depth. In order for this technology to be useful for remote monitoring and assessment, a strong correlation between the change in frequency and increasing scour depth needed to be present. The analysis indicated that, as the modal frequency increased, the correlation between scour depth and eigenfrequency decreased meaning that the higher frequencies, 11.09-Hz and 13.51-Hz in sand and 12.40-Hz in silt, are not conducive to the remote assessment of scour (Figures 7 and 8, respectively). While these higher frequencies are not conducive for use in remote assessment of scour, they do have potential uses for assessments of vehicular traffic and structure (Costley et al. 2012).

The best correlation between frequency change and scour depth for dense sand and silt can be seen in Figures 9 and 10, respectively. Note that high correlation exists for the plots corresponding to 2.65 Hz in dense sand and 2.40 Hz in silt. This corresponds well to the 2.1 Hz mode at +/-0.5 Hz resolution seen in the original study for this bridge by Diaz-Alvarez et al. (2009) and McKenna et al. (2009a and 2009b).

Interstate 20 (I-20_{LA}) Bridge over the Mississippi River in Vicksburg, MS

The eigenfrequencies of the I-20_{LA} Bridge were then analyzed to determine the frequency change in each mode for the deep foundation scenario. In the silt, 3.74 Hz was found to be the only mode with a detectable change (Figure 11). In sand, the highest degrees of variability were detected at 5.01 Hz (Figure 12) and 7.09 Hz, 10.6 Hz, and 10.91 Hz (Figure 13).

Figure 7. Frequency vs. scour depth for initial frequencies of 11.09 Hz, 13.51 Hz in sand for spread footing.

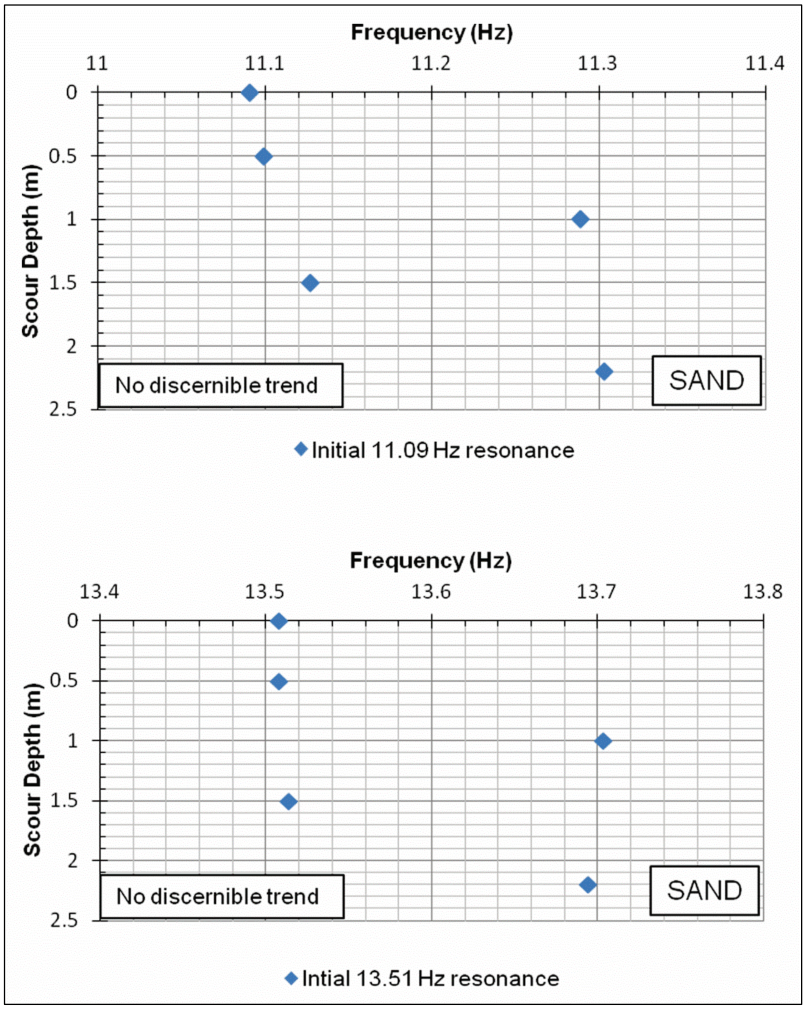


Figure 8. Frequency vs. scour depth for initial frequency of 12.40 Hz in silt for spread footing.

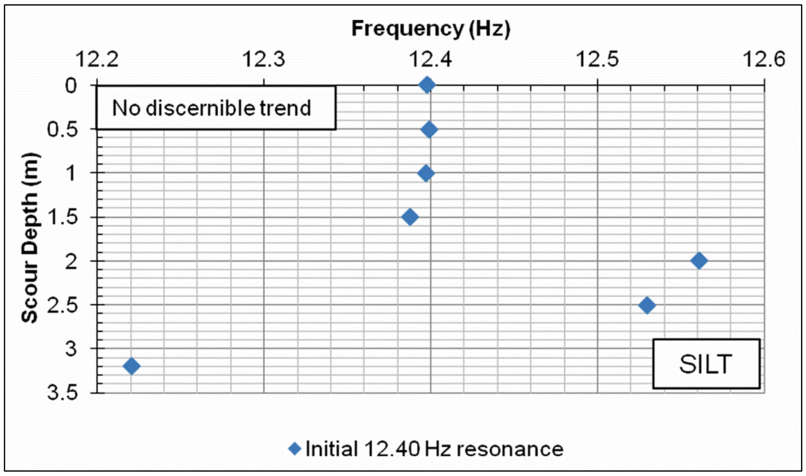


Figure 9. Frequency vs. scour depth plots for 2-D dense sand case for spread footing with good correlations between changes in eigenfrequency and scour depth.

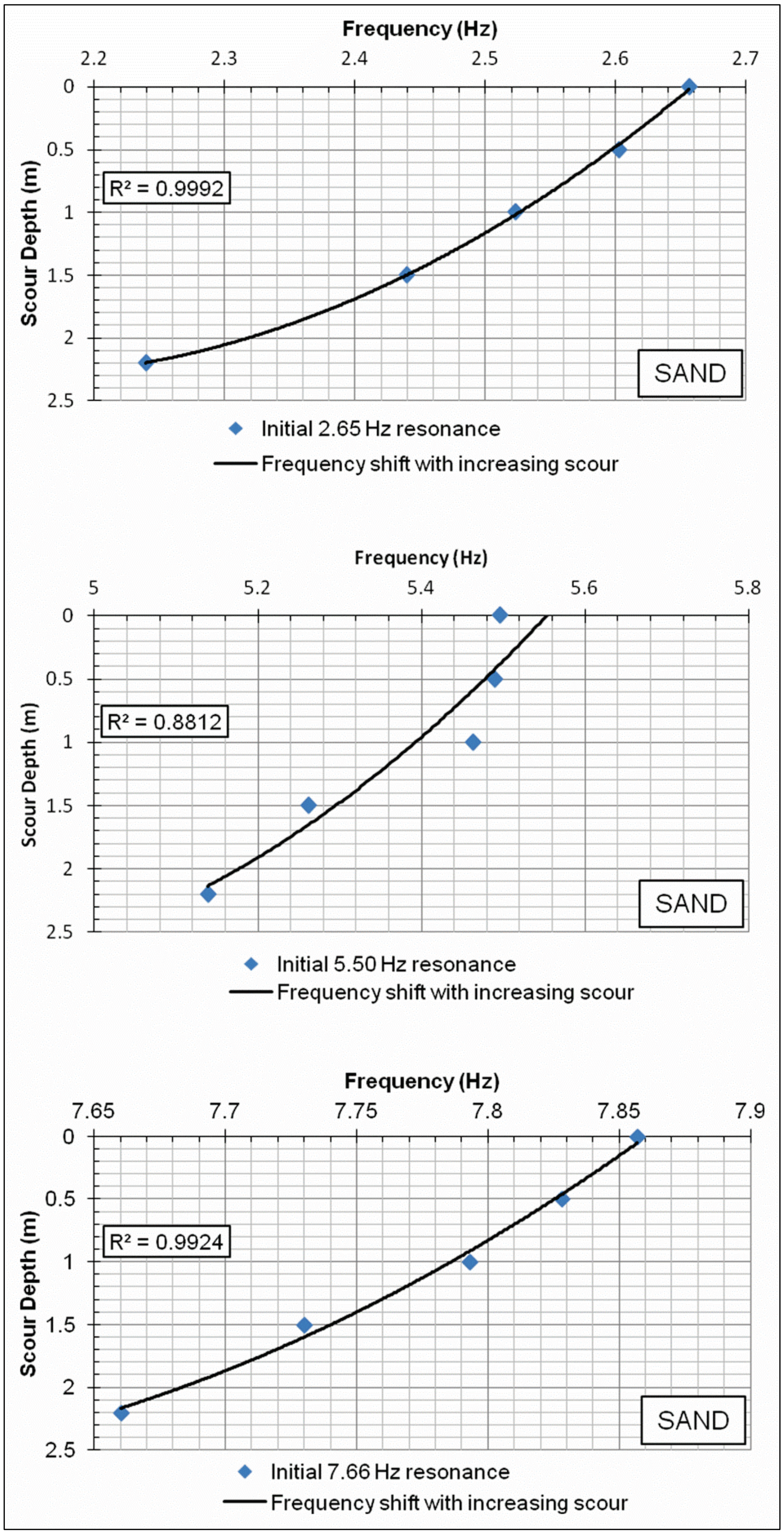


Figure 10. Frequency vs. scour depth plots for 2-D silt case for spread footing with good correlations between changes in eigenfrequency and scour depth.

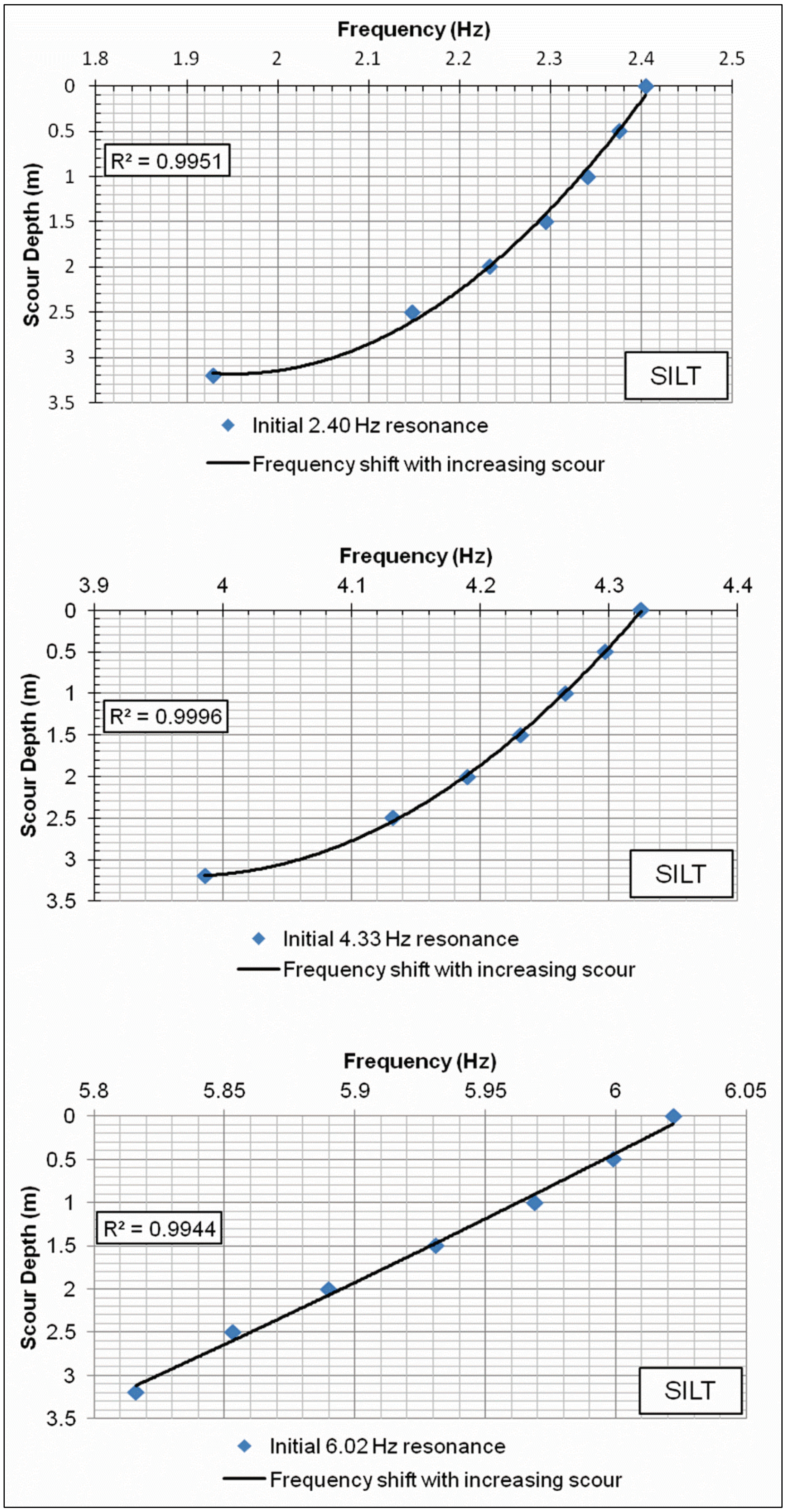


Figure 11. Frequency vs. scour depth plots for 2-D silt case for pile foundation with good correlations between changes in eigenfrequency and scour conditions.

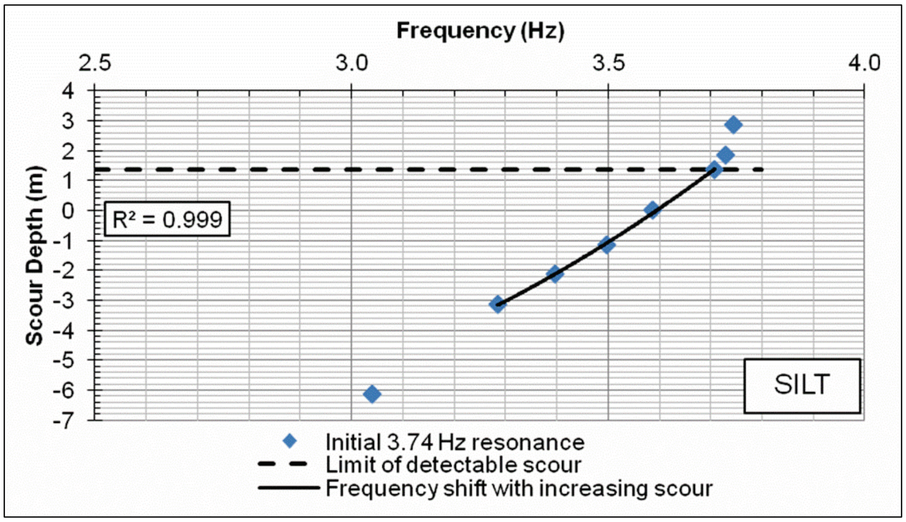


Figure 12. Frequency vs. scour depth for initial frequency of 5.01 Hz in dense sand for pile foundation.

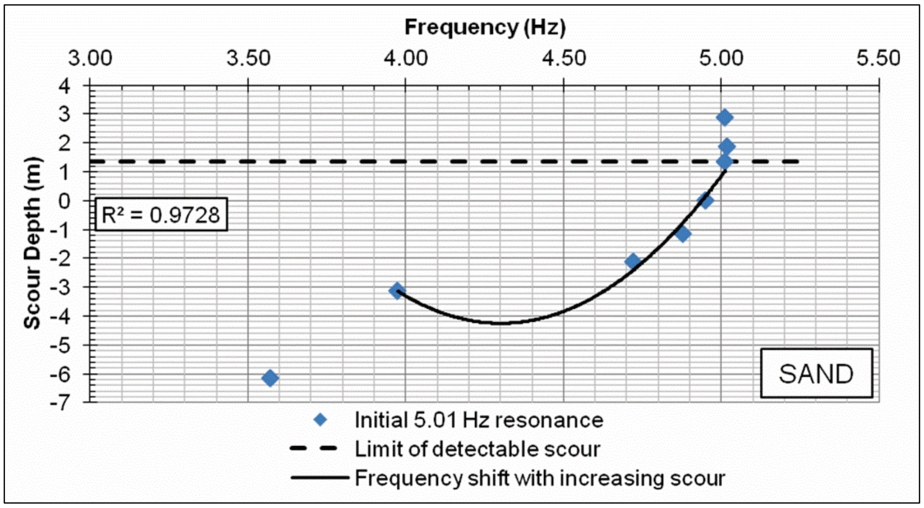
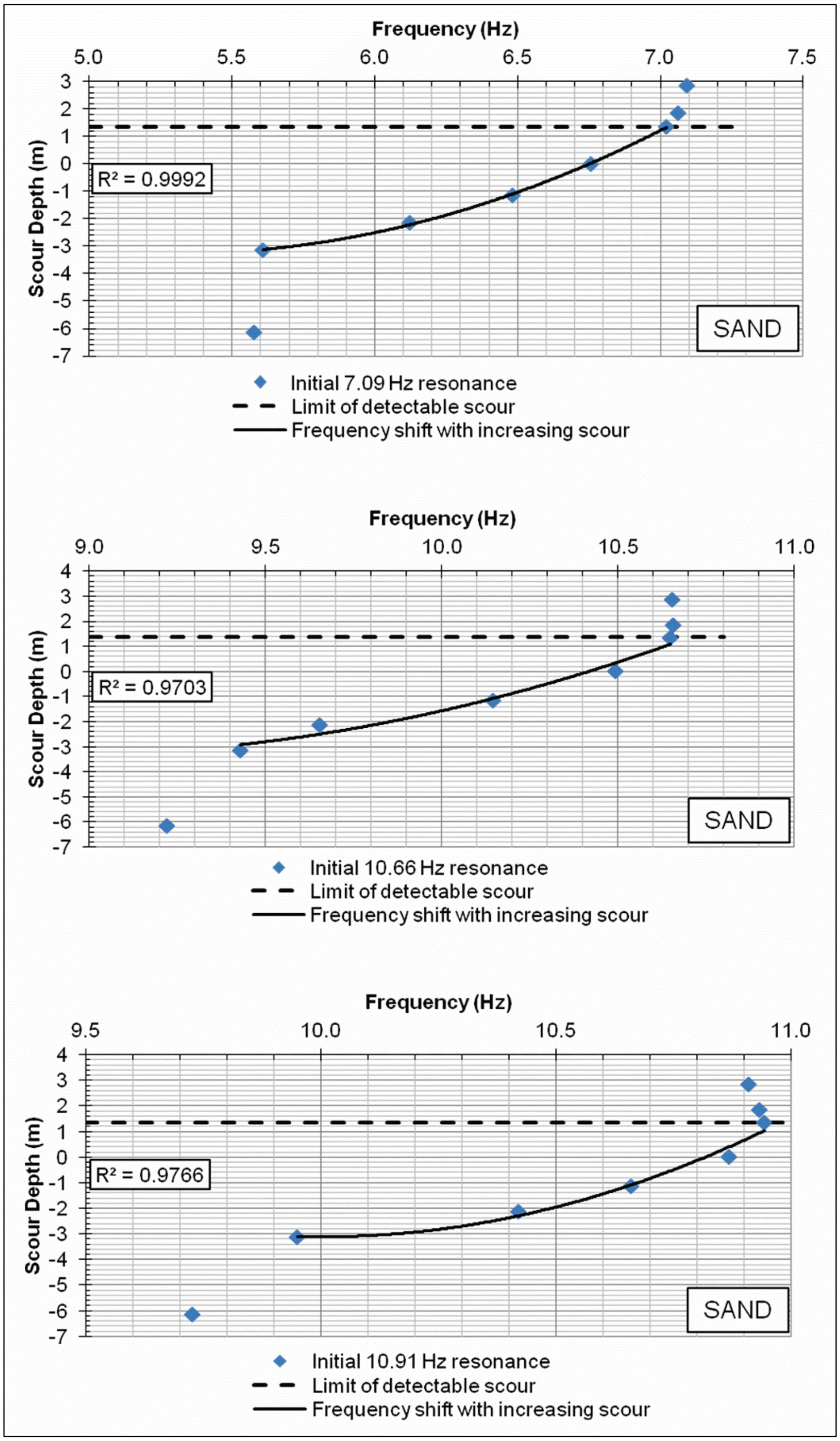


Figure 13. Frequency vs. scour depth plots for 2-D silt case for pile foundation with good correlations between changes in eigenfrequency and scour conditions.



The analysis illustrated that, while detectable, the 5.01 Hz signal was not as conducive for scour assessment purposes because it lacked a strong correlation between the change in frequency and the depth of scour (Figure 12). This modal frequency appears to correspond to the vertical deformation of the pier, likely as a result of the slight cohesion of the silt, while the modal frequencies represented in sand appear to correspond to the translational deformation of the pier. In both the silt and sand plots, a limit of detectability became apparent at 1.36 m (dashed line in Figures 11 through 13), corresponding to the middepth of the footing. As with the shallow foundation case, the variation between the change in frequency and the scour depth follows a second-order polynomial decay. However, in the case of the deep foundation, this decay continues to a critical depth corresponding to 3 m of exposed pile at which point the change in frequency is minimal, regardless of the change in depth of scour (Figures 11, 12, and 13). It is hypothesized that this critical depth corresponds to the decrease in pile buckling capacity as the unsupported pile length increases through scour of supporting material. This trend is still observed in silt, but is much less pronounced and is likely due to a slight cohesive strength.

Comparison of ERDC results with other research

The use of vibration characteristics of a structure for damage evaluation has long been a topic of worldwide research (Ko et al. 2010; Samizo et al. 2007; Kim et al. 2003; Farrar et al. 2000; Doebling et al. 1996). Studies have also been conducted concerning the use of vibration characteristics to assess scour at a bridge pier (Lee et al. 2012; Elsaid and Seracino 2012; Ko et al. 2010; Samizo et. al 2007). Samizo et al. (2007) investigated the use of microtremors during flood conditions to define the natural frequencies of bridges, which in turn were used to assess the structural integrity of bridge piers during flood conditions. Elsaid and Seracino (2012) expanded on vibration-based damage detection (VBDD) techniques in laboratory testing of an idealized structure representing a two-span continuous structure to determine the sensitivity of VBDD techniques for scour detection. Results of the modal analysis of the idealized structure revealed that, of the vertically displaced mode shapes and horizontally displaced mode shapes, only the horizontally displaced mode shapes were sensitive to scour. They concluded that, as the scour depth increased, the natural frequency decreased due to a decrease in the stiffness of the structure resulting from the scour.

Ko et al. (2010) investigated the effects of foundation scour on the vibration characteristics of two highway bridges with known scour problems in Taiwan. Their research began with finite element (FE) models of a simplified bridge structure with varying degrees of scour represented by removal of spring elements used to model the soil. Modal analysis of the FE models indicated that motion in the horizontal longitudinal and horizontal transverse directions were dominant. Field vibration measurements were then made for two bridges with known scour problems, which verified the use of change in vibration characteristics to indicate increasing scour depth.

The results obtained by ERDC researchers using both finite element modeling and field measurements of the Ft. Leonard Wood railroad truss in the original study agree with those found by other researchers including frequency decreasing with increasing scour, lower modes corresponding to changing scour conditions, and horizontal movement being the dominant motion corresponding to the lower modal frequencies. The significant difference between the ERDC researchers and others investigating the change in fundamental frequency to detect and assess scour is that the frequencies measured by ERDC's researchers utilized infrasound rather than sensors placed on the structure. Where other researchers have a variety of instruments on the bridge piers to monitor the changes in frequency of the bridge as scour occurs, infrasound allows for detection from a tactical distance. Further investigation into continuous scour monitoring is ongoing.

4 Investigation of Buckling Capacity for Interstate 20 (I-20$_{LA}$) Bridge

The results for the deep foundation case show a distinct level of scour, referred to here after as critical depth, beyond which the change in frequency is minimal regardless of scour depth. The initial hypothesis was that this critical depth, located at 3 m of exposed pile, corresponded to pile buckling. To test this hypothesis, the buckling capacity of a pile was calculated using Euler's buckling equation (Equation 12):

$$P_c = \frac{\pi^2 EI}{\left(KL_u\right)^2} \tag{12}$$

Because the piles are concrete filled pipe piles, the effective stiffness of the pile, EI_{eff}, must be calculated. Different methods for calculating this effective stiffness exist, and four were used here as a means of comparing results for this study: a weighted average, American Institute of Steel Construction (AISC) provisions, American Concrete Institute (ACI) provision, and American Association of State Highway and Transportation Officials (AASHTO) provisions. Equations 13 through 16 show the equations that were used.

$$EI_{eff} = \frac{E_s A_s + E_c A_c}{A_s + A_c} \tag{13}$$

$$EI_{eff} = E_s I_s + C_3 E_c I_c \text{ by AISC provisions} \tag{14a}$$

$$C_3 = 0.6 + 2\left(\frac{A_s}{A_c + A_s}\right) \leq 0.9 \tag{14b}$$

$$EI_{eff} = E_s I_s + \frac{0.2 E_c I_g}{1 + \beta_d} \text{ by ACI provisions} \tag{15}$$

$$EI_{eff} = E_s I_s + 0.4\left(\frac{E_c A_c}{A_s}\right) I_s \text{ by AASHTO} \tag{16}$$

where E, I, and A are the elastic modulus, the moment of inertia, and the area of the materials and sections in question, respectively. The subscripts *s, c,* and *g* refer to the properties of steel, concrete, and gross concrete section. The effective stiffness was calculated using the properties appropriate for the pile specified in the design drawings. After calculating the effective stiffness, the depth to fixity for the pile was calculated in Figure 17 as:

$$1.8\left[\frac{E_p l_w}{n_h}\right]^{0.2} \text{ by AASHTO provisions} \qquad (17)$$

where E_p is the modulus of elasticity of the pile in ksi, l_w is the weak axis moment of inertia in ft^4, and n_h is the rate of increase of the soil modulus with depth. The effective length factor, K, was taken as 2.0. This depth to fixity was added to the unbraced length due to scour. Using these criteria, Table 2 summarizes the results obtained for the buckling load, P_c.

Table 2. Buckling load in tons for each method considered.

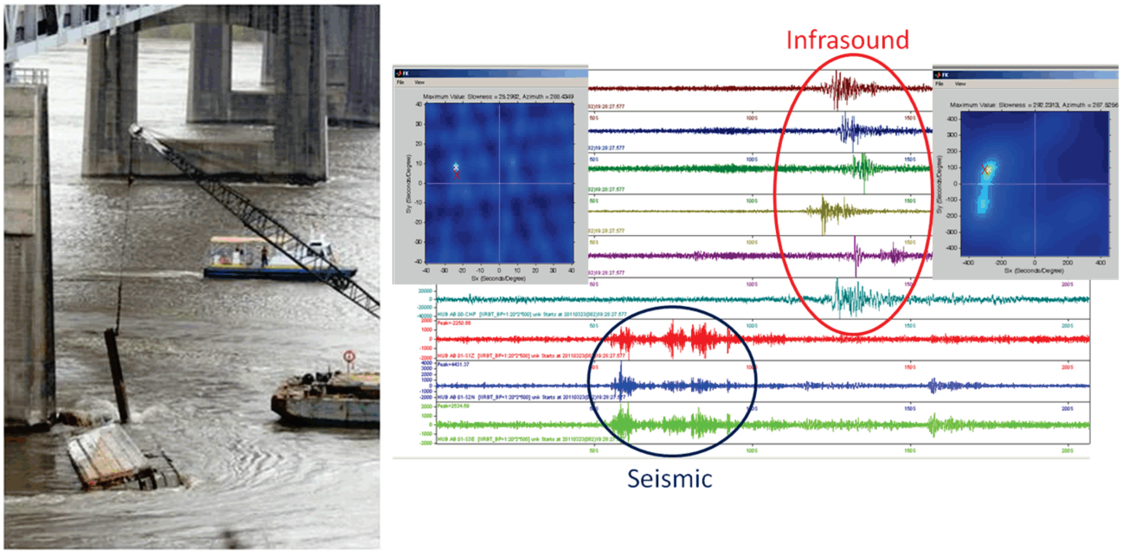
Method	Buckling Load (tons)
Weighted average	840
AISC provision	979
ACI provision	799
AASHTO provision	965

According to the design specifications, the piles were tested to 160 tons. Given the load calculated, the physical phenomenon seen at the critical depth cannot be buckling. Investigation on the significance of this critical depth is ongoing.

5 Riverine Health Assessment

Recent periods of record flooding along the Mississippi River indicate that infrasound can be used to investigate river system health during times when conventional monitoring is not possible. The permanent array in Vicksburg, MS, detected two anomalies during the historic 2011 Mississippi River flood. The first of these involved a barge strike on one of the piers of the Interstate 20 (I-20LA) Bridge in Vicksburg, MS. On March 23, 2011, a barge broke free from mooring lines, crashed into one of the I-20LA bridge piers, and sank. This event was recorded by both the seismic and infrasound sensors of the DAMES Array (Figure 14). This event is discussed in detail in Jordan et al. (2013). The study compares data obtained from instrumentation located on the structure with data obtained through the use of the seismic-acoustic array located on the ERDC campus in Vicksburg, MS, 3.7 km from the bridge. In the case of the barge strike, the infrasound array yielded more information concerning the health of the structure than onsite systems and instrumentation.

Figure 14. Seismic and infrasound detection of a barge strike on the I-20 bridge pier during the Mississippi River flood of 2011.



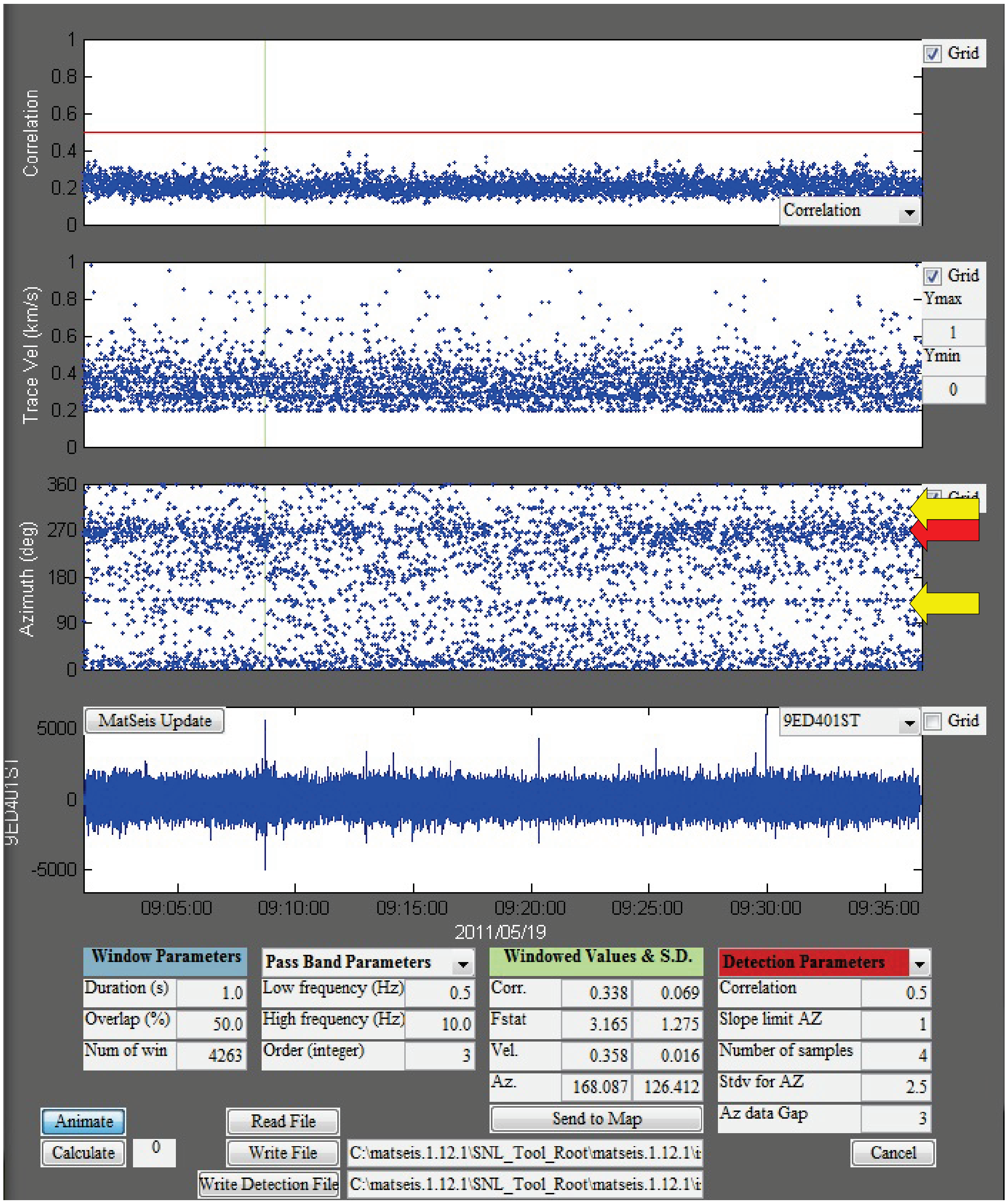
The seismic sensor located the barge strike as a point event, but the infrasound sensors recorded the event as a smear of energy, as seen in Figure 14. This smear of energy tracks with the surface of the river south of the bridge and could indicate several things. This could be the effect of vortex eddies and significant current changes immediately following the event caused by the barge's being wedged against the pier, which would also be an indicator of potential scour. The smear of energy could also be an increase in force against the eastern bank related to a change in river flow. Investigation of this anomaly is ongoing.

The DAMES Array at Vicksburg also detected a previously unrecorded signal that correlated to the confluence of the Yazoo Diversion Canal and the Mississippi River (Figure 15).

Figure 15. Previously unrecorded signal correlated to the confluence of the Yazoo Diversion Canal and the Mississippi River.

This signal appeared only after the Mississippi River had reached flood stage during the Mississippi River flood of 2011. It was initially hypothesized that this signal might correspond to the river equivalent of surf infrasound on the bend in the river and/or be a result of strong currents in the region from the increased flow volume and velocity (Garcés et al. 2006 and 2003). To confirm that this signal was actually a result of the flooding, infrasound data from two points in time were compared. Figure 16 shows the data from May 19, 2011. This date corresponds to the crest of the Mississippi River in Vicksburg, MS, during the flood of 2011, which was the highest stage on record.

Figure 16. Infrasound data for May 19, 2011 from the Vicksburg, MS, array.



Ymax 1
Ymin 0

Window Parameters	
Duration (s)	1.0
Overlap (%)	50.0
Num of win	4263

Pass Band Parameters	
Low frequency (Hz)	0.5
High frequency (Hz)	10.0
Order (integer)	3

Windowed Values & S.D.		
Corr.	0.338	0.069
Fstat	3.165	1.275
Vel.	0.358	0.016
Az.	168.087	126.412

Detection Parameters	
Correlation	0.5
Slope limit AZ	1
Number of samples	4
Stdv for AZ	2.5
Az data Gap	3

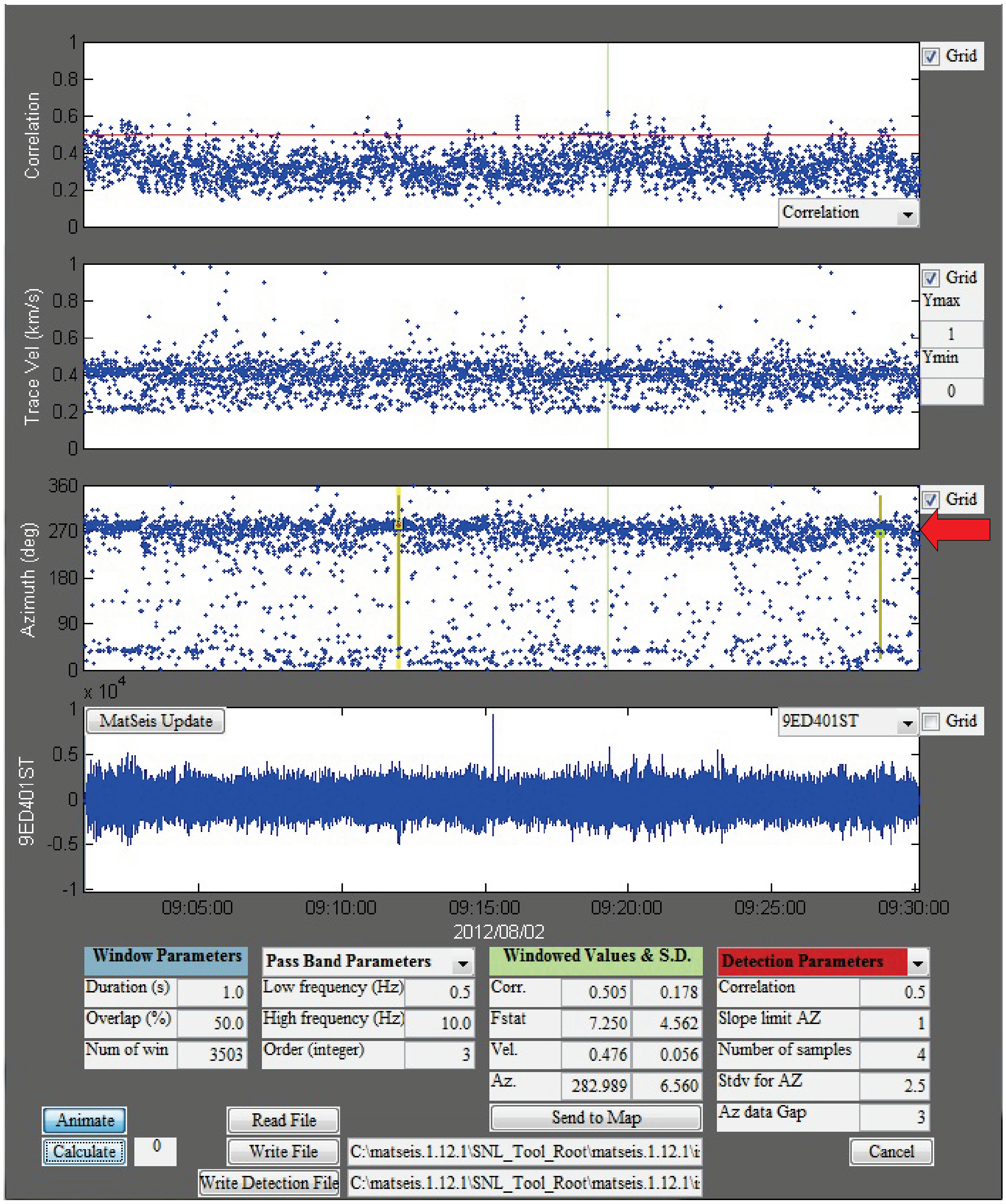
Calculate 0

Write File C:\matseis.1.12.1\SNL_Tool_Root\matseis.1.12.1\

Write Detection File C:\matseis.1.12.1\SNL_Tool_Root\matseis.1.12.1\

The strong band at an azimuth of 287° indicated with the red arrow on Figure 16 corresponds to the bridges crossing the Mississippi River in Vicksburg, MS. The two yellow arrows indicate the previously unrecorded signal. The top yellow arrow indicates the signal at azimuth 315°, which corresponds to the bend in the river at the confluence of the Mississippi River and the Yazoo Diversion Canal. The second yellow arrow at azimuth 135° represents the alias of the signal at 315°. Figure 17 shows the data from August 2, 2012. This date represents one of the lowest recorded stages for the Mississippi River at Vicksburg, MS, during the drought of 2012.

Figure 17. Infrasound data for August 2, 2012 from the Vicksburg, MS, array.



Window Parameters	
Duration (s)	1.0
Overlap (%)	50.0
Num of win	3503

Pass Band Parameters	
Low frequency (Hz)	0.5
High frequency (Hz)	10.0
Order (integer)	3

Windowed Values & S.D.		
Corr.	0.505	0.178
Fstat	7.250	4.562
Vel.	0.476	0.056
Az.	282.989	6.560

Detection Parameters	
Correlation	0.5
Slope limit AZ	1
Number of samples	4
Stdv for AZ	2.5
Az data Gap	3

Calculate: 0

Write File: C:\matseis.1.12.1\SNL_Tool_Root\matseis.1.12.1\i

Write Detection File: C:\matseis.1.12.1\SNL_Tool_Root\matseis.1.12.1\i

In comparing the two sets of data, the signal at azimuth 287° (marked with a red arrow on Figure 17 as well) that corresponds to the bridges is apparent in both sets of data, but the signal at azimuth 315° is not present when the river is low. Investigation into the limits of when this signal is present and what it represents is ongoing.

6 Conclusions and Implications

The original study looked at shallow foundations, specifically for a steel, through-truss railroad bridge over the Little Piney River in Ft. Leonard Wood, MO. The pier for this bridge was modeled first in two dimensions and then in three dimensions. The 2-D modeling compared with observational data indicated that scour detection around bridge piers was possible using the eigenfrequency change in fundamental vibrational modes. A comparison of the 2-D results and the 3-D results then revealed that the lowest frequency fundamental changes, a result of scour, were accurately represented by 2-D plane strain. The degree of scour was modeled as a changing boundary condition. This change resulted in a loss of stiffness in the substructure, thereby causing variability with resonance frequency of the structure. A distinct correlation between the change in eigenfrequency and the depth of scour was observed when the data were plotted. In addition, these lower frequencies correlated well with the most detectable infrasound frequency, indicating that the potential for the use of infrasound for remote scour detection and monitoring is present for shallow foundations.

The initial study on shallow foundations was then extended to a deep foundation case, a pile foundation. The initial hypothesis was that deep foundations would show a higher differential in eigenfrequency as the scour depth increased, compared to the shallow foundation case. Of the two soil types considered, this proved true only in the dense sand case and only to a specific equivalent free-standing pile length. The small degree of cohesion present in the silt case made this observation less pronounced. For the pile foundation case, a limit of detectable scour corresponding to the footing middepth was observed in all cases. Beyond this point, the eigenfrequency steadily decreased with depth until a depth corresponding to 3 m of exposed piling was reached. Below this depth, the change in frequency was minimal regardless of the increase in scour depth. This critical depth was hypothesized to be the result of a loss in buckling capacity due to an increased unsupported pile length. Investigation of buckling capacity for the pile foundation showed that the critical depth was not buckling. This depth could still be considered a critical depth that indicates a change in scour depth critical enough to warrant a special inspection—particularly if it coincides with a high flow event. The data indicate that the potential for the use of infrasound for remote scour detection and monitoring is also present for pile foundations.

In addition to using infrasound as a means of remotely monitoring bridges with scour problems, research indicates that infrasound may also be a means of riverine health monitoring. Two events, a barge strike and a new signal appearing during the Mississippi River flood of 2011, were recorded by the DAMES Array in Vicksburg, MS. Data from the infrasound array at Vicksburg indicated a new signal present only during flood stage and corresponding to a bend in the river and the confluence of the Mississippi River and the Yazoo Diversion Canal. Both of these events provide additional research opportunities using infrasound.

Infrasound provides an option for truly remote monitoring of bridges with noted scour problems while eliminating some of the more common problems associated with other monitoring processes. For example, on-site monitoring is limited to one discrete point in time, when the inspector is present at the bridge, and is used when only occasional measurements are needed, such as during flood events or other infrequent events. Fixed monitoring systems attempt to rectify this issue but are costly and are subject to damage and vandalism. Additionally, scour is cyclical in nature, with the most severe point occurring during high flow events—events that prohibit an onsite inspection and can damage fixed monitoring systems due to hazardous conditions.

A single infrasonic system can potentially continually monitor all the structures from tens to hundreds to even thousands of kilometers depending on source strengths. This allows for omnidirectional, persistent monitoring of large areas with a minimal investment in hardware. This can provide the bridge owner the ability to monitor multiple bridges at any given time while reducing the expense of continued visual inspections over time. Infrasound monitoring cannot only provide seasonal data but also act as an early-warning system of significant changes to the lateral stiffness of the bearing stratum during high hazard events. The use of infrasound for remote monitoring has the potential to become an alternative to traditional methods of scour assessment in order to comply with the monitoring stipulations for scour critical and/or unknown-foundation bridges.

This report concludes the proof-of-concept phase in researching the applicability of infrasound arrays to detect and assess scour at bridge piers. Two cases—a shallow foundation and a deep foundation—in this proof-of-concept study were investigated and results for each indicated that infrasound for remote monitoring of scour is a possibility. Future research will look to determine the applicability of this technique to common bridge types and will investigate the limiting factors, such as span type and bridge length, on the use of infrasound for scour detection and assessment.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* May 2016	**2. REPORT TYPE** Report 6 of a series	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE
Infrasound Assessment of Infrastructure Report 6: Scour Detection and Riverine Health Assessment Using Infrasound

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
R. Danielle Whitlow, Oliver-Denzil S. Taylor, Mihan H. McKenna,
and Meghan C. L. Quinn

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Engineer Research and Development Center
Geotechnical and Structures Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER

ERDC/GSL TR-09-16

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Headquarters, U.S. Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSOR/MONITOR'S ACRONYM(S)
USACE

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

A previously initiated proof of concept study using infrasound to detect changes in the vibrational modes of a bridge caused by scour was extended to include three-dimensional (3-D) models of a shallow foundation case and of a deep foundation case. Comparisons were made between the two-dimensional (2-D) and 3-D cases of the shallow foundation, and the results showed that plane-strain conditions represent the lowest frequency fundamental modal changes. As such, a 2-D model of the bridge substructure can be used to realistically simulate progressive scour conditions while reducing the overall computational requirement. Results from the analysis of the deep foundation case proved the potential of the use of infrasound for scour detection for pile foundations. Also included are investigations into the correspondence of the critical depth seen in plots for deep foundations with pile buckling capacity and riverine health assessment using infrasound.

15. SUBJECT TERMS (see reverse)

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED		42	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

15. SUBJECT TERMS (concluded)

Infrasound
Remote assessment
Scour
Bridges
Foundations and piers
Mississippi River Foundations
Three-dimensional modeling
Nondestructive testing
Scour at bridges
Railroad bridges
Fort Leonard Wood
Missouri
Structural dynamics