Bridge Scour Detection of the Feather River Bridge in Yuba City, CA through the use of Finite Element Modeling and Infrasound

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Abstract: Ongoing studies by the US Army Engineer Research and Development Center (ERDC) are investigating infrasound as a means of persistent monitoring and scour detection at bridges through analysis of the frequency change of the structure caused by altered boundary conditions. Large infrastructure, including bridges, resonate at their fundamental frequencies which are typically in the passband (0.1-20 Hz range) best suited for detection utilizing infrasound. A recent field deployment in Yuba City, CA allowed for characterization of scour on a known scour-critical structure with validation from a comparison of infrasound data and numerical modeling. Through the use of COMSOL, finite element models have been developed of the Feather River Bridge to investigate the fundamental frequencies of the bridge superstructure and substructure. As future research is conducted using COMSOL Multiphysis, predictions can be made on how the bridge will resonate based on the intensity of the scour.

Keywords: Structures, Resonate, Frequencies, Infrasound, Bridges

1. Introduction

Ongoing studies by the US Army Engineer Research and Development Center (ERDC) are investigating infrasound, low-frequency acoustics, as a means of scour detection and assessment at bridge piers. Scour at bridge piers and abutments is a commonly encountered issue for both military and civil works structures. Current research involves the Feather River Bridge in Yuba City, CA. A recent field deployment will allow characterization of scour on a known scour-critical structure with validation from a comparison of infrasound data, numerical modeling, and previously conducted on-site inspections.

A Finite Element model has been developed for the multi girder bridge located in Yuba City, CA. The model was constructed using 3-D Euler beam elements representing the superstructure members. This model is being used to investigate the frequency of the bridge's main spans 21-22, Figure 1, out of the 24 total spans. These two spans were the main focus for the COMSOL model due to maximum span length and scoured pier location.

Figure 1. Multi-girder Bridge (Feather River Bridge) in Yuba City, CA. The upper photo highlights the two spans of interest for the study, span 21 (left) and span 22 (right).

A second finite element model has been partially developed for the scoured pier. Initially, the model consisted of the original drawings of the bridge pier without the retrofit and was fixed at the bottom of the pier. Modifications will be made in the future to include the updated retrofit and the earth surrounding the base of the pier based on the scour records. Making these few adjustments will affect how the natural frequency of the pier vibrates.

1.1 Infrastructure Assessment through the use of Infrasound

Infrasound is a low frequency sound (0.1 to 20 Hz range) that can propagate over long distances with low attenuation, meaning the signal is still clear on arrival after long travel distances. This ability to propagate long distances without losing signal characteristics may provide a means of monitoring from a distance.

Infrasound is produced by many natural sources such as earthquakes, tornadoes, volcanoes, and etc. (Bedard and Georges 2000; Evers and Haak 2010). Infrasound is also generated by manmade sources, including infrastructure. Large infrastructures, such as bridges, radiate frequencies whether natural or driven that are detectable through the use of infrasound (McKenna et al. 2009a, 2009b; Kobayashi 1999; Donn et al. 1974). A study conducted by the US Army ERDC investigating a steel truss railroad bridge supported the idea of infrasound for infrastructure detection and assessment when the bridge was detected at an array located 27km from the structure (Diaz-Alvarez et al. 2009).

2. Monitoring Scour through the use of Infrasound

During the study of the Fort Leonard Wood truss bridge, only the superstructure was considered, and the base of the piers was modeled as an idealized pin connection. In cases where scour is not present, this is a valid assumption, leading to good results from the model. However, for a structure that has a scour issue, such as the Feather River Bridge, the substructure must be considered. The removal of bed material causes a changing boundary condition which changes the fundamental frequencies at which the structure resonates.

2.1 Proof-of-Concept

Using the substructure of the Fort Leonard Wood Bridge as a proof-of-concept case, a scour condition was simulated using two different types of soil while varying the scour level from zero scour to a total scour condition. Analysis at each scour level increment showed a change in frequency. The results showed that as scour increased, the frequency of the structure decreased. This once again proved that infrasound could potentially be used as an infrastructure assessment tool, this time to also monitor scour. (Whitlow et al. 2013)

3. Finite Element Model of Feather River Bridge

The superstructure and substructure were modeled using COMSOL to determine the fundamental modal frequencies of the structure under dead load.

For the multi-girder bridge model, Figure 2, the 3 dimensional Euler Beam elements were used. The bridge was modeled with a pinned connection at each end of the main spans as well as between span 21 and span 22. A 9-inch shell element was added to the spans to represent the deck. The frame is made of steel and the deck in concrete.

For the pier model, Figure 3, the solid mechanics element was used. A concrete material was used for the pier and the entire bottom of the pier was fixed.

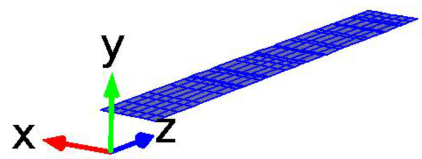

Figure 2. 3-D Euler Beam Multi-girder Bridge Model

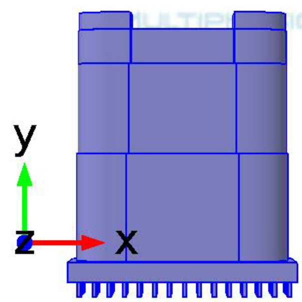

Figure 3. 3-D Model of Pier 22 using the Solid Mechanics Element

All models were created using the drawings of the Feather River Bridge provided by California Department of Transportation (Caltrans).

3.1 Finite Element Model Frequencies compared to Infrasound Frequencies using SAP2000

An initial simplified finite element analysis was completed using SAP2000 to identify what frequencies were related to the structure. The frequencies seen using the structural software are provided in Table 1 below. Figure 4, shows the spectra of the infrasound signal from the Feather River Bridge. Each color shown represents a different frequency peak which was identified as 1.09 Hz, 1.48 Hz, 1.79-1.87 Hz, and 2.26 Hz.

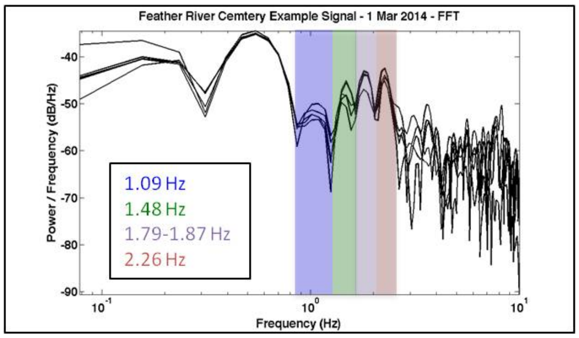

Figure 4. Frequencies of bridge processed from cemetery array location

Table 1: First six modes found of simplified bridge model using SAP200

Mode	Frequency (HZ)
1	1.04
2	1.06
3	1.10
4	1.20
5	1.37
6	1.59

3.2 Finite Element Model Frequencies compared to Infrasound Frequencies using COMSOL

The FE model of the superstructure (Spans 21-22) determined the fundamental modal frequencies of the structure under dead load.

A 9in concrete deck was added to span 21-22 of the superstructure and the finite element analyses determined fundamental modes of 1.31 Hz resonance, Figure 5, for vertical vibration and 1.65 Hz resonance, Figure 6, vibrating in torsion. All superstructure frequencies were found within the first six modes and observed in the infrasound field data.

An acoustic model of the bridge, Span 22, was developed to determine what energy the structure is producing. An initial substructure finite element model analysis was successful, but improvements to the boundary conditions are predicted to affect the resonant frequency of the piers.

The data processed from the cemetery (FRC) array shows frequencies that are comparable to the frequencies found from the simplified bridge model. The vertical mode (1.31 Hz) is comparable to the SAP2000 program but is around a 12% difference from what the FRC array shows. Further processing of the data could show a 1.30 Hz. The torsion mode (1.85 Hz) is seen in the FRC array processed data.

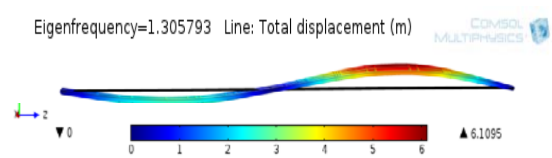

Figure 5. Spans 21-22, Deck vibrating vertically with a 1.31 Hz resonance

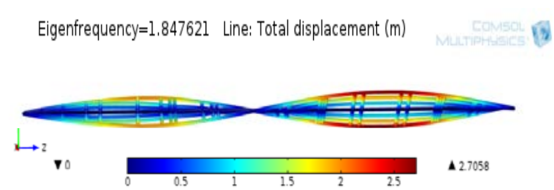

Figure 6. Spans 21-22, Deck vibrating in torsion with a 1.85 Hz resonance

4. Case Study of the Feather River Bridge in Yuba City, CA

Once the proof-of-concept was completed and it was known that the change in frequency could be indicative of the amount of scour, a bridge was needed to begin a case study for field validation. The Feather River Bridge is a steel plate multi girder bridge built in 1945 consisting of 24 spans for a total length of 2,674 ft. This bridge is scour critical and has documented scour issues from previous large flow events. A scour evaluation was made for the three main channel piers in 2002, this would include piers 21-23. These three piers are the supports for the spans being modeled in this paper, spans 21 and 22.

4.1 Infrasound setup for Feather River Bridge

For these experiments ERDC uses a light-weight deployable system of seismic-infrasound-acoustic-metrological (SIAM) arrays. These arrays monitor omnidirectional ranges of 5-200 km. Multiple arrays collect a better data set and allow for triangulation of source. For the Feather River Bridge experiment, three arrays were deployed.

The first array was set up 1.6 km southeast of the bridge (FRA), the second array was set up 24 km southeast of the bridge (FRB), and the third array was set up 2.6 km northeast of the bridge (FRC) as seen in Figure 7. These arrays collected data for seven full days. Weather balloons were launched in six hour increments for a twenty four hour period to collect pertinent meteorological data used in data analysis.

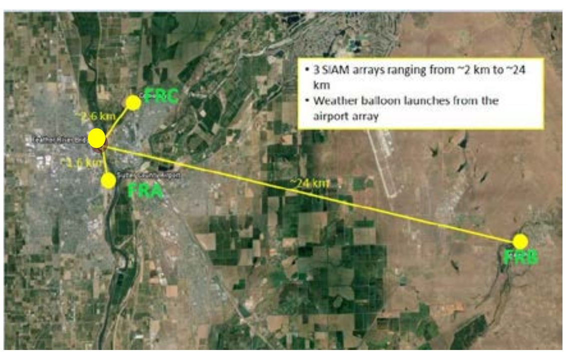

Figure 7. SIAM Array Locations

4.2 Processing of SIAM Array Data

Initial data processing utilized InfraTool (Hart et al. 2004) to identify by hour, times of coherency across each array as well as a backazimuth for the detections. A time varying, continuous-wave signal was identified and signal characteristics were further investigated using GeoTool (Coyne et al. 1995).

The backazimuths for the coherent hours identified in InfraTool corresponded to a band which aligns with the Feather River Bridge location from 209° to 224°, Figure 8. This identified day and time were investigated for packetized signals in GeoTool with the signal filtered using a 3-pole Butterworth filter between 1 and 4 Hz (Figure 9), with the frequency range indicated by finite element modeling discussed in a future section. Fourier analysis on the identified signal packets confirmed coherency across the array in the expected frequency range. Frequency wave number analysis then confirmed the signal source at the backazimuth of the Feather River Bridge.

Additional filtering of some background noise will be needed to locate the bridge from all arrays and to investigate other coherent signals.

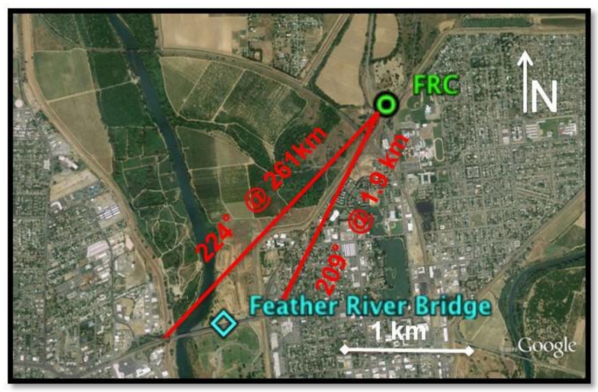

Figure 8. Feather River Bridge was localized using the backazimuth of the signal seen from array FRC.

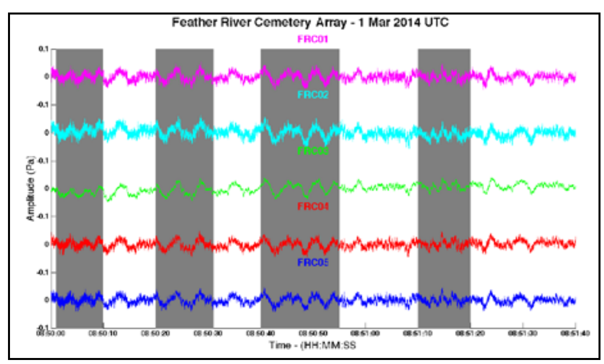

Figure 9. Feather River Bridge signal collected on array FRC.

5. Conclusions

Modal frequencies from the finite element analysis of the superstructure and backazimuth to source confirm the infrasound signals identified in the collected field data are associated with the Feather River Bridge.

6. References

1. Bedard, A. J. and T.M. Georges. 2000. Atmospheric Infrasound. Physics Today. March, 2000. pp 32-37.

2. Coyne, J. M. and I. Henson. 1995. Geotool Sourcebook: User's Manual. PL-TR-96-2021, Sponsor: Advanced Research Projects Agency (DoD), Nuclear Monitoring Research Office.

3. Department of the Army. 2002. FM 3-34.343 Military Nonstandard Fixed Bridging. Washington D.C.

4. Diaz-Alvarez, H., M. H. McKenna, and P. Mlakar. 2009. *Infrasound Assessment of Infrastructure; Report 1, Field Testing and Finite Element Analysis for Railroad Bridge A.B 0.3, Fort Leonard Wood, Missouri*. ERDC/GSL TR-09-16. U.S. Army Engineer Research and Development Center. Vicksburg, MS.

5. Evers, L., and H. Haak. 2010. *The characteristics of infrasound, its propagation and some early history.* Edited by A. Le Pichon et al., Infrasound Monitoring for Atmospheric Studies, pp. 3-28.

6. Hart, D. 2004. Automated Infrasound Signal Detection Algorithms Implemented in MatSeis – Infra Tool. SAND2004-1889.

7. Ko, Y.Y., W.F. Lee, W.K. Chang, H.T. Mei, and C.H. Chen (2010). “Scour Evaluation of Bridge Foundations Using Vibration Measurement.” Proceedings of the Fifth International Conference on Scour and Erosion. 7-10 November 2010. San Francisco, California.

8. McKenna, M. H., S. Yushanov, K. Koppenhoefer, and J. R. McKenna. 2009. *Infrasound Assessment of Infrastructure; Report 3, Numerical Simulation of Structural Acoustic Coupling and Infrasonic Propagation Modeling for Rail Road Bridge A.B 0.3, Fort Leonard Wood, Missouri*. ERDC/GSL TR-09-16. U.S. Army Engineer Research and Development Center. Vicksburg, MS.

9. McKenna, M. H., A. F. Lester, and S. McComas. 2009. *Infrasound assessment of infrastructure; Report 2, Experimental Infrasound measurements of Rail Road Bridge A.B 0.3, Fort Leonard Wood, Missouri.* ERDC/GSL TR-09-16. Vicksburg, MS, U. S. Army Engineer Research and Development Center

10. Richardson, E.V. and S.R. Davis. 2001. Evaluating *Scour at Bridges*, Hydraulic Engineering Circular No. 18, 4th ed, FHWA NHI 01-001, Federal Highway Administration, Washington, D.C.

11. Taylor, O-D.S., R.D. Whitlow, and M.H. McKenna. “Scour Detection and Riverine Health Assessment Using Infrasound”. Proceedings of Symposium on the Application of Geophysics for Engineering and Environmental Problems (SAGEEP). March 19, 2013. Denver, CO.

12. Whitlow, R.D., M.H. McKenna, O.D.S Taylor, R.D. Costley, M.C.L. Quinn, and H. Diaz-Alvarez (2012). *Infrasound Assessment of Infrastructure; Report 4, Investigation of Scour Using Infrasound for Railroad Bridge A.B. 0.3, Fort Leonard Wood, Missouri*. ERDC/GSL TR-09-16. U.S. Army Engineer Research and Development Center. Vicksburg, MS.

13. Whitlow, R.D., A.M. Jordan, S.L. McComas, H. Diaz-Alvarez, and M.H. McKenna. “Structural Infrasound: A scour case study of the Feather River Bridge.” 2014 Meeting of the Military Sensing Symposia (MSS) Specialty Group on Battlespace Acoustic, Seismic, Magnetic, and Electric-Field

Sensing and Signatures (BAMS). Springfield, VA. October 28-31, 2014.

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