Real-time Seismic Monitoring of the New Cape Girardeau (MO) Bridge

by

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ABSTRACT

The Bill Emerson Memorial Bridge in Cape Girardeau (MO), a new Mississippi River crossing, is a cable-stayed bridge approximately 80 km from the epicentral region of the 1811–1812 New Madrid earthquakes. This seismically active region requires hazard mitigation programs, including those related to investigation of strong shaking of structures and the potential for ground failures in the vicinity of structures. Design of the bridge accounted for the possibility of a strong earthquake (magnitude 7.5 or greater) during the design life of the bridge. A state of the art seismic monitoring system for this bridge is now implemented and is described herein.

The seismic instrumentation plan for the bridge includes 84 accelerometers on the superstructure and pier foundations (caissons, tower and deck), in the vicinity of the bridge (*e.g.* free-field, both surface and downhole), and in horizontal spatial arrays to assess the differential motions at the piers along the 1206 m (3956 ft) span of the bridge. The real-time seismic monitoring system supports signal transmission via the internet from combinations of uniaxial and tri-axial accelerometers to the recorders at the site. The system records events at the site and broadcasts the data to outside users. Synchronized system-wide timing is provided for all of all the accelerometers. Real-time streaming of the data enables remote maintenance and data acquisition and retrieval capabilities. In addition, wind-related sensors (e.g. anemometers) will be deployed to record the response of the bridge to wind-related vibrations.

The response data obtained from the bridge during earthquakes is aimed to be used by the owner, researchers and engineers to (1) assess the performance of the bridge, (2) check design parameters, including the comparison of dynamic characteristics with actual response, and (3) better design future similar bridges.

If desired, by appropriate configuration of the streamed data, the instrumentation can also be used as a "health monitoring" tool to (a) serve as an early warning system of defects or unexpected behavior, and (b) assess damage to the structure. Monitoring the response of structures in real-time or near real-time is usually adopted when response information is needed rapidly such as with the recent emphasis on homeland security.

KEYWORDS: real-time monitoring, cable-stayed bridge, New Madrid Seismic Zone, seismic event, acceleration, accelerometer, downhole, internet communication, data acquisition.

1. INTRODUCTION

The acquisition of structural response data during earthquakes is essential to evaluate current design practices and develop new methodologies for analysis, design, repair and retrofitting of earthquake resistant structural systems, including lifelines such as bridges. This is particularly true in urban environments of seismically active regions.

In order to understand structural responses thoroughly, it is also necessary to record ground motions at the free-field in the vicinity of the structure to study soil-structure interaction (SSI) effects.

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The New Madrid area, where the great earthquakes of 1811–1812 occurred, is a seismically active region requiring earthquake hazard mitigation programs, including those related to investigation of strong shaking of structures and the potential for ground failures in the vicinity of structures (Nuttli, 1974; Woodward-Clyde Consultants, 1994). The Bill Emerson Bridge (here in after, the Cape Girardeau Bridge), in service since December 2003, is located approximately 80 km due north of New Madrid, Missouri (Figure 1). Design of the bridge (a) accounted for the possibility of a strong earthquake (magnitude 7.5 or greater) during the design life of the bridge and, as a result (b) was based on design response spectrum anchored to a zero-period acceleration (ZPA) of 0.36 g with a 10 % probability of being exceeded in 250 years (Woodward-Clyde, 1994). A general schematic of the bridge is shown in Figure 2.

Leading institutions that collaborated in the financing and development of the seismic instrumentation of the Cape Girardeau Bridge are: Federal Highway Administration (FHWA), the United States Geological Survey (USGS), Missouri Department of Transportation (MoDOT), the Multi-disciplinary Center for Earthquake Engineering Research (MCEER) and a selected commercial vendor.

2. OBJECTIVES AND GOALS OF THE ARRAY

The objective of this paper is to present details of the state-of-the-art seismic monitoring scheme which employs an extensive number of sensors deployed on and in the vicinity of the new Cape Girardeau Bridge. Consultation for developing an instrumentation plan for the Cape Giradeau Bridge among FHWA, MoDOT, MCEER, USGS and other institutions began in 1996, at about the time the contract for construction was awarded. At that time, a decision was made not to develop and implement a continuous recording instrumentation scheme but rather an instrumentation scheme, that would trigger and record above a prescribed threshold of motion. Such an approach would have simplified the configuration of hardware and data collection units. However, recent developments in digital technology allow configuration of the system such that:

1. real-time streaming, viewing and recording of structural response became feasible. This capability provides three basic and important advantages:

   a) in addition to recording strong-motion events, it is possible to selectively record continuous and real-time low-amplitude response data, as needed, with relative ease by manual recording or manually scheduled recording.

   b) use of the near real-time information can help make informed decisions related to the response and performance of the bridge. This capability maybe construed and configured as “monitoring the health of the structure”.

   c) maintenance of the system will be readily and easily enhanced as any malfunction of the sensors and related hardware will be detected via the real-time streamed information.

2. automatic recording after certain threshold of response at a particular location of the instrumented structure is reached.

Although there may be other objectives that may require special purpose instruments and hardware (*e.g.* sensors tailored for health monitoring such as fiber optics, etc.), for seismic engineering studies, in general, three main categories in recording motions are sought. In planning for the overall instrumentation scheme, it is deemed important to clearly identify these categories:

1. instrumentation of the superstructure and pier foundations.
2. instrumentation of the free-field in the vicinity of the structure including those related to downhole measurements and horizontal spatial arrays to assess the differential motions at the piers of the long span structure.
3. ground failure arrays in the vicinity of the

structure.

The instrumentation currently deployed addresses only the first and partially the second categories. Due to fiscal constraints, ground failure arrays were kept outside of the scope of this project.

3. ESSENTIAL RESPONSES TO CAPTURE

This array of accelerometers facilitate recording motions of and assessing the following responses of the bridge and its vicinity:

1. Freefield motions at the surface and downhole locations reaching competent (i.e. unweathered) rock.
2. Overall motion of the cable-stayed bridge.
3. Motions of the (a) two towers, to assess their translational and torsional behavior – relative to the caissons and deck levels and (b) the deck, to assess the fundamental and higher mode translational (longitudinal, transverse and vertical) and torsional components.
4. Motions at the extreme ends of the bridge and intermediate pier locations to provide data for the translational, torsional, and rocking soil-structure interaction (SSI) at the foundation levels. This setup also provides insight into the horizontal and vertical spatial variation of ground motion.

4. SPECIAL CONSIDERATIONS

4.1 Physical and Scheduling Constraints

When planning for the instrumentation of this bridge, the designated design high water level at an approximate elevation of 108.1 m (354.7 ft) had to be considered because the tops of caissons of Piers 2, 3 and 4 can be under water. Since the U. S. Coast Guard, which has regulatory authority, requires that everything be above 108.1 m (355 ft), the idea to plan for the deployment of sensors on the top surface of some of the caissons were abandoned. In addition, the contractor did not allow any detailed deployment during the construction phase. Therefore, only the absolutely necessary work (e.g. generic conduits for downhole at Piers 2 and 3, and a length-wise conduit to accommodate cabling later) were placed during the construction.

4.2 Special Considerations for Weather

It is essential to consider the general weather requirements for the instrumentation. The Cape Girardeau area is often subjected to severe thunderstorms and lightning. Therefore, lightning protection for the seismic instruments has been provided. In addition, while the current instrumentation plan was not developed to provide for extensive wind engineering components, future deployment of anemometers, rainbuckets and barometric pressure and temperature gauges have been recommended (N. Jones, *pers. comm., 2002):*

Another concern is wind-induced vibrations of the cables of the cable-stayed bridge. A separate study was conducted to measure wind-induced cable-response (H. Bosch, FHWA, *pers. comm*., 2002). As a result, it is expected that additional sensors may be deployed to capture specific wind effects.

5. SENSORS, RECORDERS AND LOCATIONS

The hardware for the seismic monitoring of the bridge consists of EpiSensor[2] accelerometers, Q330[2] digitizers, and data concentrator and mass storage devices (herein called Baler[2]s) with wireless communication. A schematic view of the instrumentation using wireless routers and IP

[2] Citing commercial hardware throughout this manuscript does not imply endorsement of vendors or their products. Baler is a data concentrator and mass storage unit. These units gather data and pass it to the next location as they are instructed to do so. In essence, a Baler serves as the brain and router of the data acquisition system. Baler-14 works with a single Q330 unit. Baler45 works with multiple number of Q330 units. In the case of Cape Girardeau instrumentation scheme, since there are multiple Q330 units, then only Baler45 units are used.

Cloud Technology[3] is shown in Figure 3. The Q330 digitizers are housed in a rack along with Baler45 units in each one of the hubs at Piers 2 and 3. The combination of all Q330 digitizers/recorder and Baler45 units at one location constitutes a hub (e.g. Pier 2 and Pier 3 are designated hubs). Each of the two hubs, known as multi-channel Data Acquisition Block (DAQ Block), collects and digitizes the analog signals from the accelerometers located throughout the bridge and then transmits the digitized data to the Central Recording System (CRS) using Wireless Routers that form a Wireless IP Cloud in the surroundings of the bridge. The CRS, merges the streamed data from the DAQs and records at location (on a pre-planned manner using a trigger algorithm to produce file events) and broadcasts the streamed data out using standard TCP/IP communications protocol. Block diagrams for DAQ's and CSR are provided in Figure 4.

A high-speed Internet connection makes data available to operators and users remotely by using password-protected access from authorized outside web browsers. The software package at the central recording system handles this process

The distribution of the 85 accelerometers deployed on the bridge is depicted in Figure 5. This is compatible with and optimizes the 6-channel capacities of the 14 Q330 digitizer/recording systems. With this detailed scheme, it will be possible to completely detect and define the overall global structural response of the bridge (caissons, tower and deck) as stated in the array design objectives.

Permanent surface and downhole free-field arrays are deployed, one at the Missouri and another at the Illinois side of the Mississippi River. These are in the immediate vicinity of Bent 1 and Pier 15 (within a distance of 100-300 m [~300-900 ft]). Geotechnical characteristics of the boreholes that house the triaxial downhole accelerometers are documented (Woodweard-Clyde, 1994). These free-field arrays, deemed to be without any feedback from the structure, are essential in providing the input ground motions that may be used as a surrogate for the various piers of the bridge and also for convolution and deconvolution studies of the free-field ground motion.

The general instrumentation scheme for deck locations at the centerline (CL) of the cable-stayed deck, and at the locations L1, L2, R1 and R2, is also shown in Figure 5. Sensors at these particular locations are aimed at capturing larger modal response contributions. The exact locations are based on mathematical modal analyses (S. Dyke, *written communication*, 2001). It is noted herein that deck instrumentation at Pier 2 and 3 is on deck level at elevation 124.5 m (408.4ft). At both Piers 2 and 3, the deck is supported by the cables and does not rest on the piers. There are pot bearings where the edge beams rest on the pier cap. Therefore, there is a separate set of sensors at pier elevation 121.3 m (398 ft) (Figure 3).

6. SAMPLE AMBIENT DATA

Figure 6 shows sample data acquired remotely and on demand in real-time. The signals reflect ambient vibration of the bridge, most likely caused by traffic moving on the bridge. The figure shows relative accelerations at three locations of the bridge and corresponding amplitude spectra. The data is quite noisy but still contains signals that are attributed to the structural response. For such very low-amplitude data, detailed analyses is not performed herein.

[3] A new approach used to transmit data between the hubs (DAQ's) and the CRS.

7. CONCLUSIONS AND RECOMMENDATIONS

Details of the seismic instrumentation scheme of the Cape Girardeau Bridge are presented. The scheme described provides extensive strong-motion response recording capability to facilitate different types of studies and to assess the performance of the subject structure during strong-motion events. Although the instrumentation system is intended for recording responses of the structure to moderate-to-large seismic events, it can also record low-amplitude motions (M~2-3) and wind-induced motions. Such low-amplitude motions can facilitate assessment of dynamic characteristics of the structure and provide a basis for estimating levels of shaking during stronger events, the return periods of which are longer than smaller events.

It is clear that with this planned state-of-the-art instrumentation, real-time recording and communication capability are achieved. The system provides an advantage in that the system functionality can be checked remotely.

It is hoped that the advance planning for seismic and wind instrumentation of the Cape Girardeau Bridge will set an example for future large projects in seismically active regions. By integrating seismic instrumentation into the early design stages of a structure, an owner can save resources by avoiding redundant efforts when making provisions for hardware to monitor and record vibrational responses of such important structural systems during extreme seismic events and weather conditions.

In the future, whenever feasible, sufficient additional sensors (e.g. for soil-structure interaction (SSI) or liquefaction or wind related) can be integrated into the new system.

8. REFERENCES

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ACKNOWLEDGEMENTS

Many individuals and organizations that contributed to the successful realization of the state of-the-art seismic monitoring system for the Cape Girardeau Bridge are acknowledged herein.

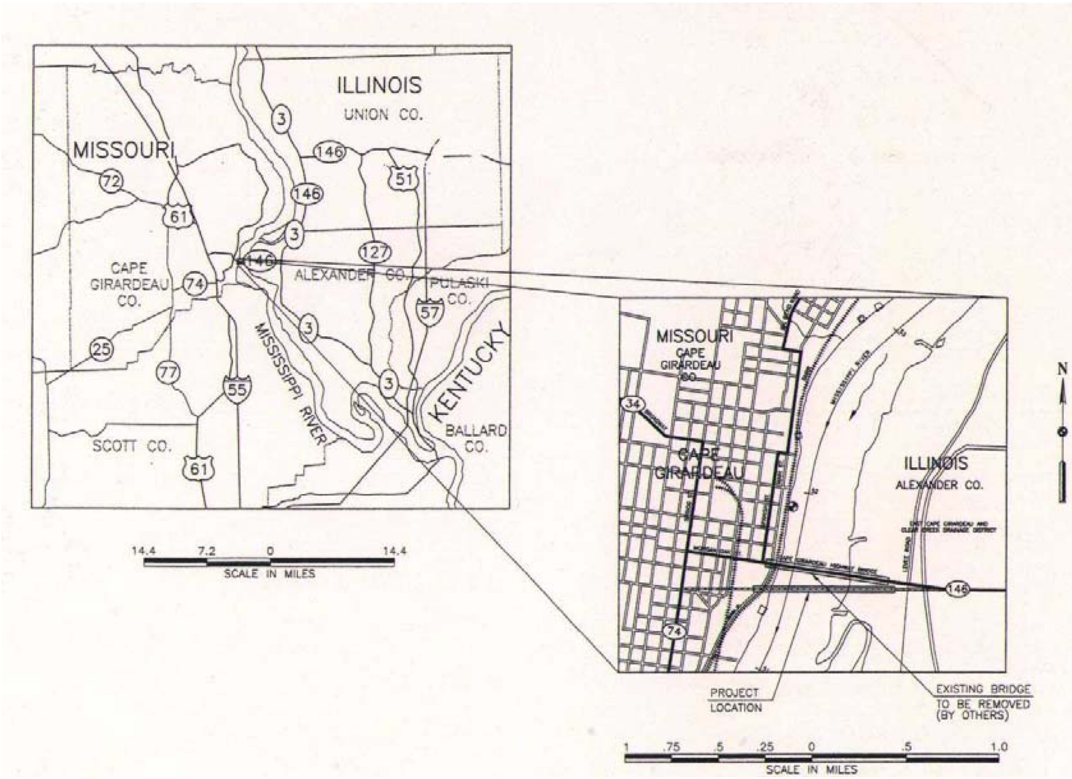

Figure 1. General location map of Bill Emerson Memorial (Cape Girardeau) Bridge

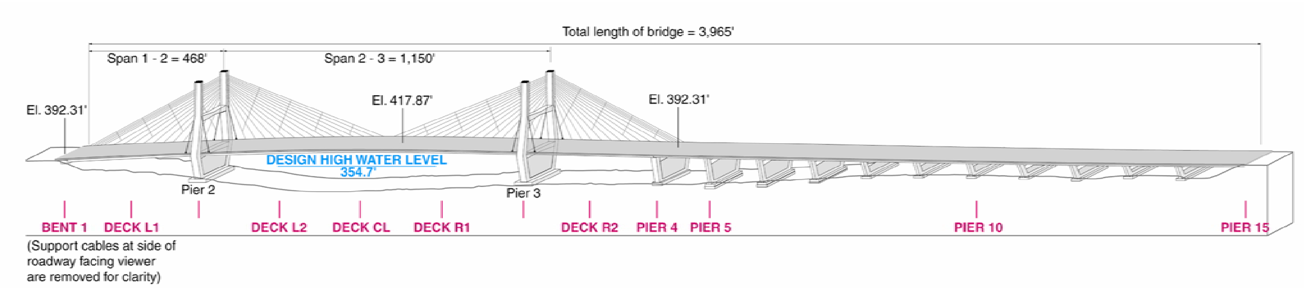

Figure 2. General schematic and dimensions of Bill Emerson Memorial (Cape Girardeau) Bridge.

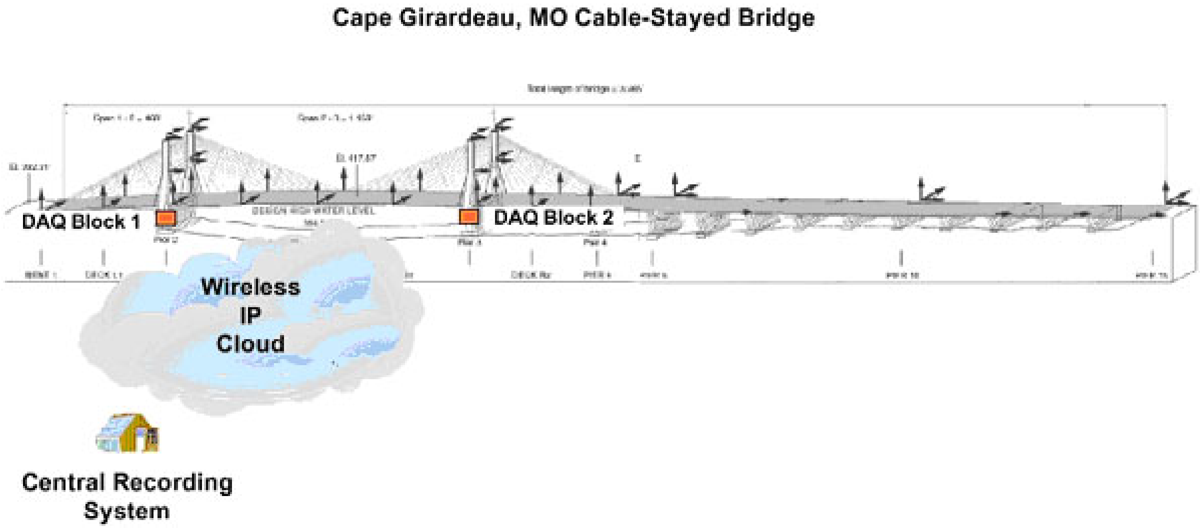

Figure 3. General Schematic of the seismic monitoring system using Data Acquistion Blocks 1 and 2 at the Piers 1 and 2, off-structure Central Recording System and wireless communication technology (Wireless IP Cloud).

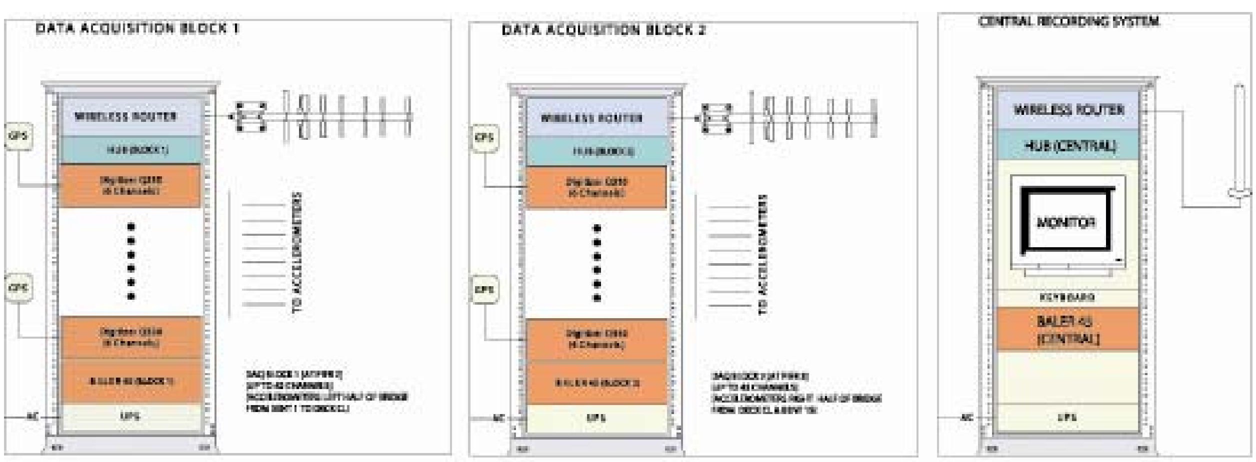

Figure 4. Schematic of details of (Data Acquisiton Blocks) DAQ’s and Central Recording System (CRS)

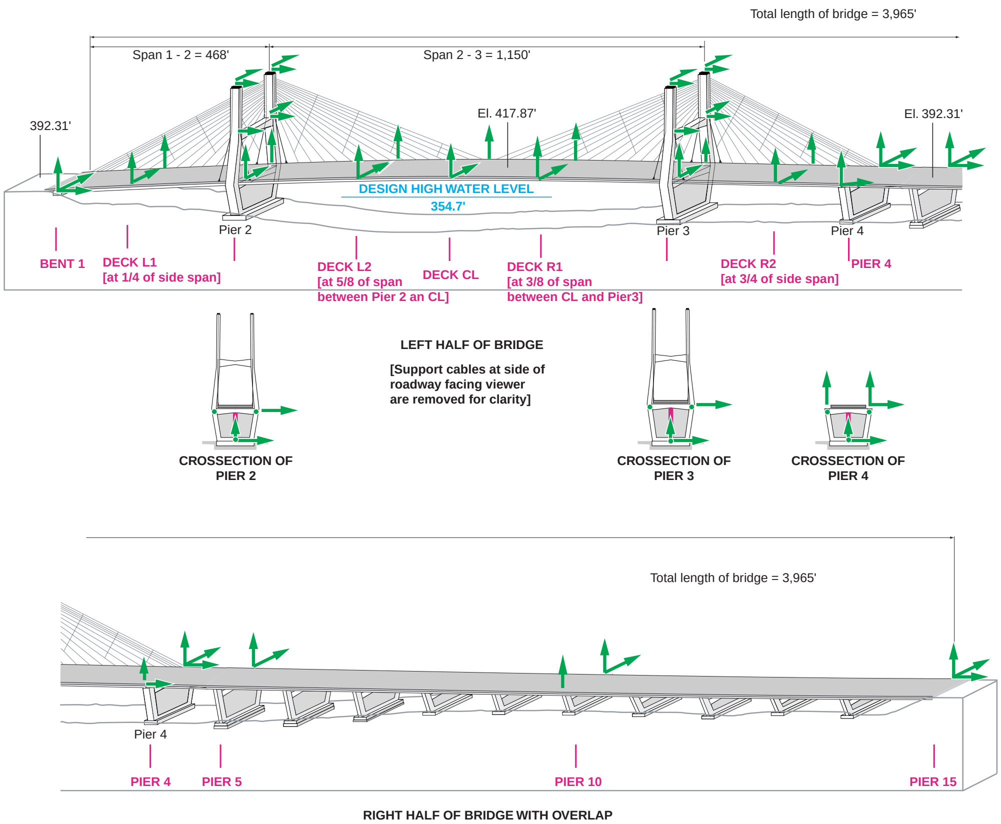

Figure 5. Enlarged three-dimensional view of the Bill Emerson Memorial (Cape Girardeau) Bridge, significant locations identified for seismic instrumentation and distribution and orientation of the accelerometers.

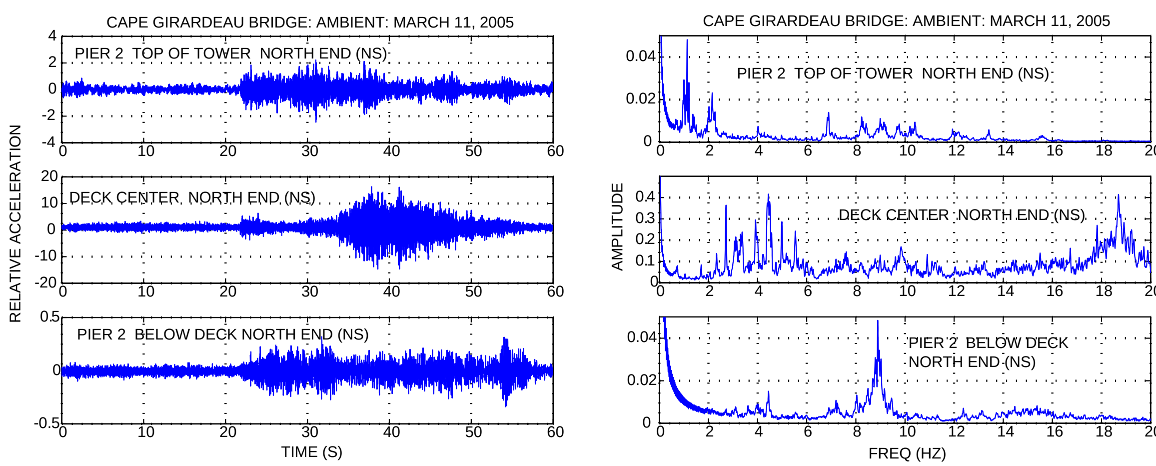

Figure 6. Sample ambient vibration response (recorded in real-time and on demand) and corresponding amplitude spectra at three bridge locations.