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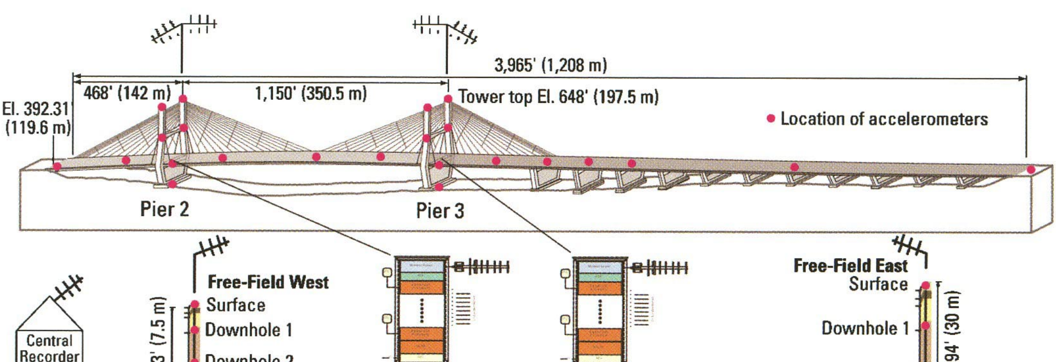
INSTRUMENTATION OF CAPE GIRARDEAU BRIDGE



Real-Time Seismic Monitoring of the New Cape Girardeau Bridge and Preliminary Analyses of Recorded Data: An Overview

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This paper introduces the state-of-the-art seismic monitoring system implemented for the 1,206-m-long (3,956 ft) cable-stayed Bill Emerson Memorial Bridge in Cape Girardeau (Missouri), a new Mississippi River crossing, approximately 80 km from the epicentral region of the 1811 and 1812 New Madrid earthquakes. The real-time seismic monitoring system for the bridge includes a broadband network consisting of superstructure and free-field arrays and comprises a total of 84 channels of accelerometers deployed on the superstructure (towers and deck), pier foundations (caisson tops and bents), and in the vicinity of the bridge (e.g., free-field, both surface and downhole). The paper also introduces the high-quality response data obtained from the broadband network that otherwise would not have been possible with older instruments. Such data 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. Preliminary spectral analyses of low-amplitude ambient vibration data and that from a small earthquake reveal specific response characteristics of this new bridge and the free-field in its proximity. There is coherent tower-cable-deck interaction that sometimes results in amplified ambient motions. Also, while the motions at the lowest (triaxial) downhole accelerometers on both Missouri and Illinois sides are practically free from any feedback of motions of the bridge, the motions at the middle downhole and surface accelerometers are influenced significantly even by amplified ambient motions of the bridge.
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INTRODUCTION

In seismically active regions, 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 for urban environments in 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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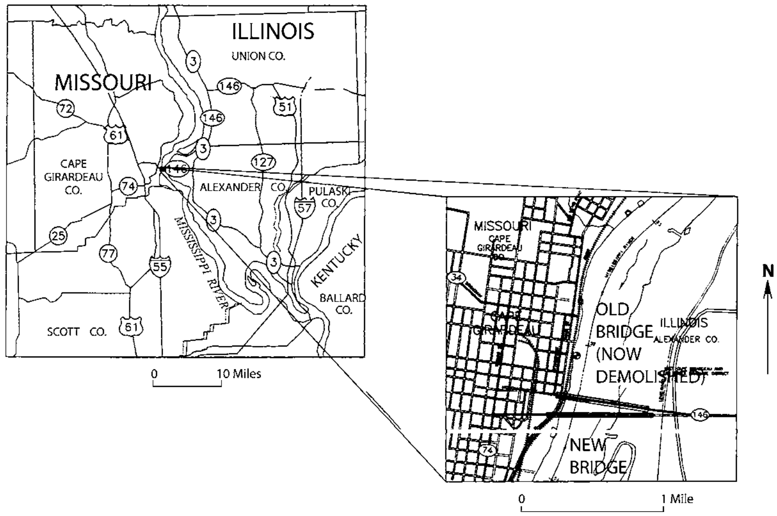

Figure 1. General location map of Bill Emerson Memorial (Cape Girardeau) Bridge.

The New Madrid area, where the great earthquakes of 1811 and 1812 occurred, is an active seismic 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 (herein 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 accounted for the possibility of a strong earthquake (magnitude 7.5 or greater) during the design life of the bridge, and as a result 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). Therefore, ideas related to seismic instrumentation of the bridge were initiated in 1996—before the contract for construction was awarded. Lead institutions that collaborated in the financing and development of the seismic monitoring plan are the Federal Highway Administration (FHWA), Missouri Department of Transportation (MoDOT), the Multidisciplinary Center for Earthquake Engineering Research (MCEER), and the United States Geological Survey (USGS).

A general schematic of the bridge is shown in Figure 2. The figure illustrates overall longitudinal dimensions of the bridge and key elevations, as well as key sensor locations alongside the bridge.

When planning for the instrumentation of this bridge, two important issues were taken into consideration:

1. 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 at Piers 2, 3, and 4 can be under water. Since the U.S. Coast Guard, which has regulatory authority,

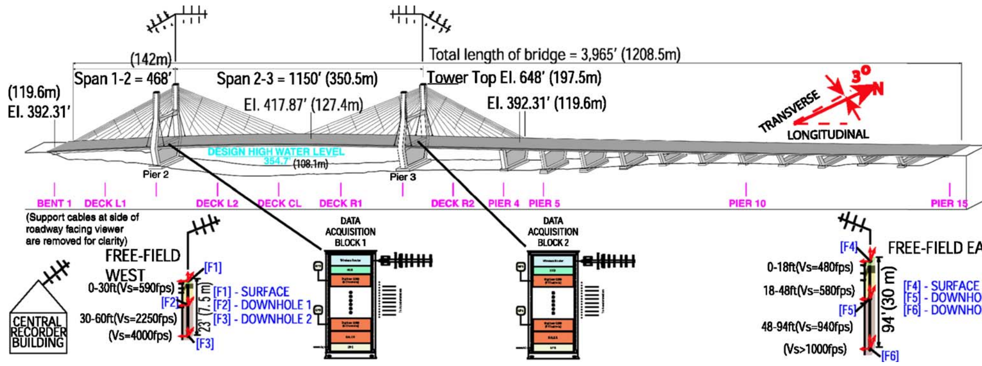

Figure 2. The figure illustrates (a) overall longitudinal dimensions of the bridge and key elevations and (b) key sensor locations alongside the bridge; (c) general schematic of the seismic monitoring and wireless communication system antennas for communicating data between different locations (e.g., to and from the data acquisition blocks 1 (housed in Pier 2 tower) and 2 (housed in Pier 3 tower) and to the off-structure Central Recording System); and (d) free-field arrays on both the Missouri and Illinois sides. (Note: Shear-wave velocities shown in fps [1 fps=0.3048 m/s]).

required that everything be above 108.1 m (355 ft), the idea to deploy sensors on the top surface of some of the caissons was abandoned. In addition, the contractor did not allow any detailed deployment during the construction phase. Therefore, only the absolute necessary work (e.g., generic conduits for downhole at Piers 2 and 3, and a lengthwise conduit to accommodate cabling later) was placed during the construction.

2. The Cape Girardeau area is often subjected to severe thunderstorms and lightning. Therefore, extensive lightning protection for the seismic instruments has been provided.

An important concern is the wind-induced vibrations of the cables of the cable-stayed bridge. 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). Furthermore, a separate study has been conducted to measure wind-induced cable-responses (H. Bosch, FHWA, pers. comm., 2002). As a result, it is expected that additional sensors and wind engineering-related hardware may be deployed to capture specific wind effects.

The objective of this paper is to introduce details of the extensive, state-of-the-art, and broadband seismic monitoring network deployed on and in the vicinity of the new Cape Girardeau Bridge. The paper also presents preliminary spectral analyses of low-amplitude ambient vibration data and that from a small earthquake. Spectral analyses processes are well described in textbooks such as that by Bendat and Piersol (1980). Recorded data by the network, even from small-amplitude motions (at $\sim 10^{-4}-10^{-3}$ g levels) caused by a small earthquake that occurred 175 km away or ambient vibrations caused by tower-cable-deck interactions, provide multifaceted opportunities for a variety of response analyses of the structure and proximate sites. For example, site response effects and soil-structure interaction are observed. Earthquake motions from the free-field are traceable to the top of tower. Conversely, the reverse phenomenon whereby ambient vibrations of the structure (tower-cable-deck interaction) cause excitations at the free field. Thus, in this introductory overview paper, using data from the network, while various sample analyses and computations are presented to provide insight into the vibrational behavior of the bridge, detailed analyses of each phenomena occurring at particular location of the bridge or the free-field sites are not intended. Earlier publication (Çelebi et al. 2004) related to this bridge did not include data analyses since data streaming started in March 2005.

There are no doubt numerous bridges in the United States and other countries that are instrumented at different levels and for different objectives. The list of instrumented bridges is too long to describe herein. It is important to mention that, in the NMSZ, there is I-40 Bridge on the Mississippi that is instrumented (Pezeshk et al. 2004). Recently, Masri et al. (2004) described a temporary health monitoring instrumentation and related data acquisition and interpretation application for the Vincent Thomas Bridge in Los Angeles (CA) by using junction box of existing 26-channels of accelerometers. They state that "sensor network of one to two orders of magnitude more sensors than are currently deployed at the bridge would be needed." Ko and Ni (2005) recently summarized technology developments in health monitoring of 20 large-scale bridges in Hong Kong and vicinity.

GENERAL OBJECTIVES

In monitoring a bridge, 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 to capture and define (a) overall motion of the cable-stayed bridge, and motions of the (b) two towers, to assess their translational and torsional behavior—relative to the caissons and deck levels and (c) the deck, to assess the fundamental and higher mode translational (longitudinal, transverse and vertical) and torsional components, and (d) extreme ends of the bridge and intermediate pier locations to provide data for the translational, torsional, and rocking SSI at the foundation levels as well as the horizontal and vertical spatial variation of ground motion.
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.

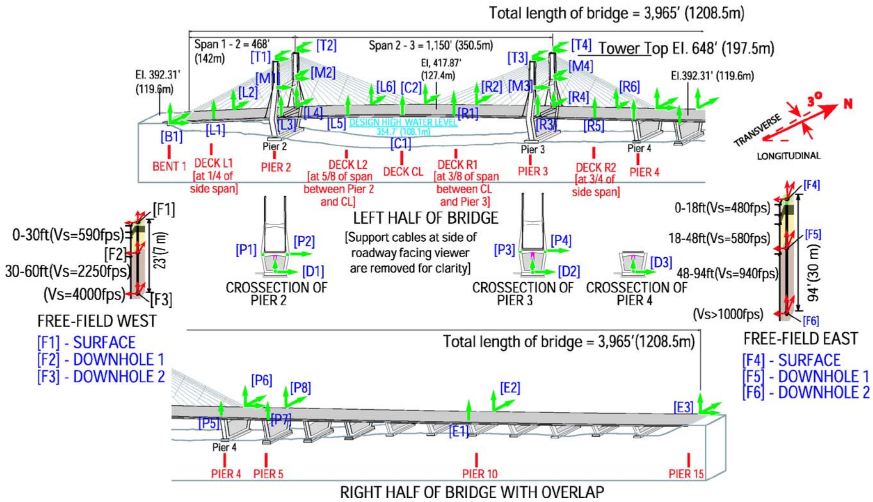

Figure 3. General schematic illustrating longitudinal dimensions of Cape Girardeau Bridge. Also shown are the locations and orientations of the accelerometers—both for the bridge and its piers and the free-field arrays on Missouri and Illinois sides. Location identifier codes (e.g., T1 for tower top location 1 [in this case south end of tower top at Pier 2]) are used for data management in general. Each arrow indicates one channel of accelerometer and its orientation.

The instrumentation currently deployed addresses only the first and second categories. Due to fiscal constraints, ground failure arrays were kept outside of the scope of this project. However, there are initiatives by geotechnical engineering researchers to add such arrays (Olson, pers. comm., 2005).

A more detailed schematic of the bridge is shown in Figure 3. In addition to dimensions, Figure 3 shows key sensor (a) locations (with identifier two-character location codes that are important for data management and for referencing motions throughout this paper) and (b) their orientations, described in more detail later in the paper.

GOALS OF REAL-TIME INSTRUMENTATION

At the time deliberations for seismic monitoring started, initially, a decision was made to develop and implement an instrumentation and recording system that would trigger and record above a prescribed threshold of motion most likely caused by an earthquake. However, subsequent developments in digital technology feasibly allowed real-time streaming, viewing, recording, and broadcasting of signals to be incorporated as well. The state-of-the-art adopted real-time capability provides three basic and important advantages:

1. In addition to recording strong-motion events, it is possible to selectively record continuous real-time low-amplitude response data, on demand, with relative ease.

2. Use of the near-real-time information can help make informed decisions related to the response and performance of the bridge. This capability may be construed and configured as "monitoring the health of the structure." For example, based on pre-established procedures and levels of motions (e.g., displacements at certain points computed from accelerations), the owner may initiate (a) inspection with or without closing the bridge and under very severe situations that indicate damage, or (b) close the bridge for repair. An application of such a monitoring system has been implemented for a building in San Francisco, California (Çelebi et al. 2004).
3. 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.

SENSORS, RECORDERS, AND LOCATIONS

The hardware for the seismic monitoring of the bridge consists of 84 channels of Kinemetrics EpiSensor[1] accelerometers, Q330[1] digitizers, and data concentrator and mass storage devices (herein called Balers[1]) with wireless communication. A schematic view of the instrumentation using wireless routers was shown in Figure 2. 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 radio transmittal via the antennas shown in Figure 2. The CRS merges the streamed data from the DAQs and records at location (in a preplanned manner using a trigger algorithm to produce file events) and broadcasts the streamed data out using standard TCP/IP communications protocol. 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. Schematic block diagrams for DAQ's that transmit data to the CRS are provided in Figure 2.

The distribution of the 84 channels of accelerometers deployed on the bridge is depicted in Figure 3. 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) and the free-field sites as stated in the monitoring design objectives. However, specific responses such as rocking of the piers cannot be detected.

Permanent surface and downhole free-field arrays are deployed, one at the Missouri

[1] 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 numbers of Q330 units. In the case of Cape Girardeau instrumentation scheme, since there are multiple Q330 units, then only Baler45 units are used.

(MO) and another at the Illinois (IL) side of the Mississippi River. The MO free-field array is approximately 100 m (~300 ft) south of Bent 1 and the IL array is approximately 300 m (~900 ft) southeast of Pier 15 (Figures 2 and 3). Geotechnical characteristics of the boreholes that house the triaxial downhole accelerometers at defined depths from the surface are qualitatively and quantitatively shown in Figures 2 and 3. On the MO side, the two downhole accelerometers are at 9 ft (~3 m) and 23 ft. (~7.5 m) from the surface. On the IL side, the two downhole accelerometers are at 47 ft (~14.3 m) and 94 ft. (~30 m) from the surface. The quaternary sediments extend from the surface to approximately (a) 75 m (245 ft) on the IL side and (b) 100 m (300−320 ft) on the MO side (Woodward-Clyde 1994). These two free-field arrays, intended 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. However, as discussed later in this paper, the data acquired to date indicates that while the lowest (triaxial) downhole accelerometers on both MO and IL sides (locations F3 and F6 in Figures 2 and 3) depict that they are practically free from any feedback of motions of the bridge, the middle downhole and surface accelerometers are not.

The general instrumentation scheme for deck locations at the centerline (CL) and at the locations L1, L2, R1, and R2 of the cable-stayed deck is also shown in Figure 3. Sensors at these four particular locations (L1, L2, R1, and R2) are intended to capture larger modal response contributions; hence their exact locations are based on modal analyses (S. Dyke, written comm., 2001). It is noted herein that deck instrumentation at Pier 2 and 3 is on deck level at elevation 124.5 m (408.4 ft). 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).

DATA MANAGEMENT

An integrated structural monitoring network of this size requires data management infrastructure and strategy. All 84 channels of data are now being transmitted to the Data Management Center (DMC) of the Incorporated Research Institutions for Seismology (IRIS) via the Antelope[2] software at the Central Recording System of the Cape Girardeau Bridge Seismic Monitoring System. IRIS is receiving the data in mini-seed format (generally used by seismologists). The latency at IRIS-DMC for all streamed data from the bridge is four to eight weeks during which all streamed data is temporarily stored and are available. After that, unless there is an earthquake, the streamed data are deleted. Identified events (earthquakes) will be windowed and permanently saved at IRIS and at National Strong Motion Program (NSMP) of the United States Geological Survey (USGS) for further processing for use by engineering community. This involves computing processed acceleration, velocity, and displacement time histories for each channel and each event. Data transmitted to and from IRIS is archived according to seed channel

[2] The Antelope software is licensed and installed at the site server by Kinemetrics. Citing commercial names does not imply endorsement of the vendor.

naming format (e.g., for this bridge: **7405.NP.HNx.LL**. Here 7405 is the station code number assigned by network operator, NP stands for NSMP as the network operator, HN indicates an accelerometer as the sensor for the particular channel, "x" is the sensor orientation (Z, 2, or 3), and "LL" is the two-character L-code (Location Code [Figures 2 and 3]) developed by the author for this particular bridge in accordance with data format requirements of the Antelope software and IRIS. All horizontal sensors oriented transverse (to the bridge) use the orientation code "2" since they are more closely aligned to NS, and longitudinal sensors have the orientation code "3" since they are more closely aligned to EW. Therefore, in this paper, directions of components of horizontal motions are hereafter referred to as NS and EW instead of lateral and longitudinal.

PRELIMINARY DATA ANALYSES

As stated earlier, one of the objectives of the paper is to introduce response data obtained from the network and subsequent preliminary spectral analyses. Therefore, three sets of data are selected:

1. Data Set 1: 267-second interval of 1 May 2005 including an earthquake is used to introduce the various bridge response characteristics and describes an anomaly in the form of resonance caused by tower-cable-deck interaction.
2. Data Set 2: 300-second duration data without an earthquake is used essentially to revalidate that the described anomaly occurs frequently.
3. Data Set 3: Earthquake data of 1 May 2005 extracted from Data Set 1 are analyzed separately to assess response to an earthquake only. Additional site response analyses are presented for this data set only.

As previously stated, much more detailed analyses of the various responses of the structure or the site are not possible in this preliminary introductory manuscript.

DATA SET 1: 267-S INTERVAL OF 1 MAY 2005 INCLUDING AN EARTHQUAKE

An earthquake (M=4.1) occurred at 12:37:32 (UTC) on Sunday, 1 May 2005. The epicenter, 175 km from the bridge, was located at 6 km (4 miles) SSE (162°) from Manila, AR (with epicentral coordinates 35.830°N, 90.150°W). The hypocentral depth was estimated to be 10 km (~6 miles).

Figures 4 and 5 show the series of filtered acceleration data plotted in groups to logically interpret relative response issues. The 267-second length of the record plotted represents neither the duration of the earthquake nor the strong shaking caused by the earthquake. Such long-duration shaking at this site from a small earthquake that occurred 175 km away is caused by crustal reverberations and surface waves (Hanks 2005).

Figure 4 shows full 267 seconds and all three components of acceleration data from MO and IL free-field arrays. The figure depicts the following:

- Earthquake record of 1 May 2005 is between 30 and 130 seconds of the 267-second-long data plotted in Figures 4 and 5. Most of the length of the "earthquake" response records is caused by surface waves.
- During earthquake shaking, the motions at locations of the middle downhole ac-

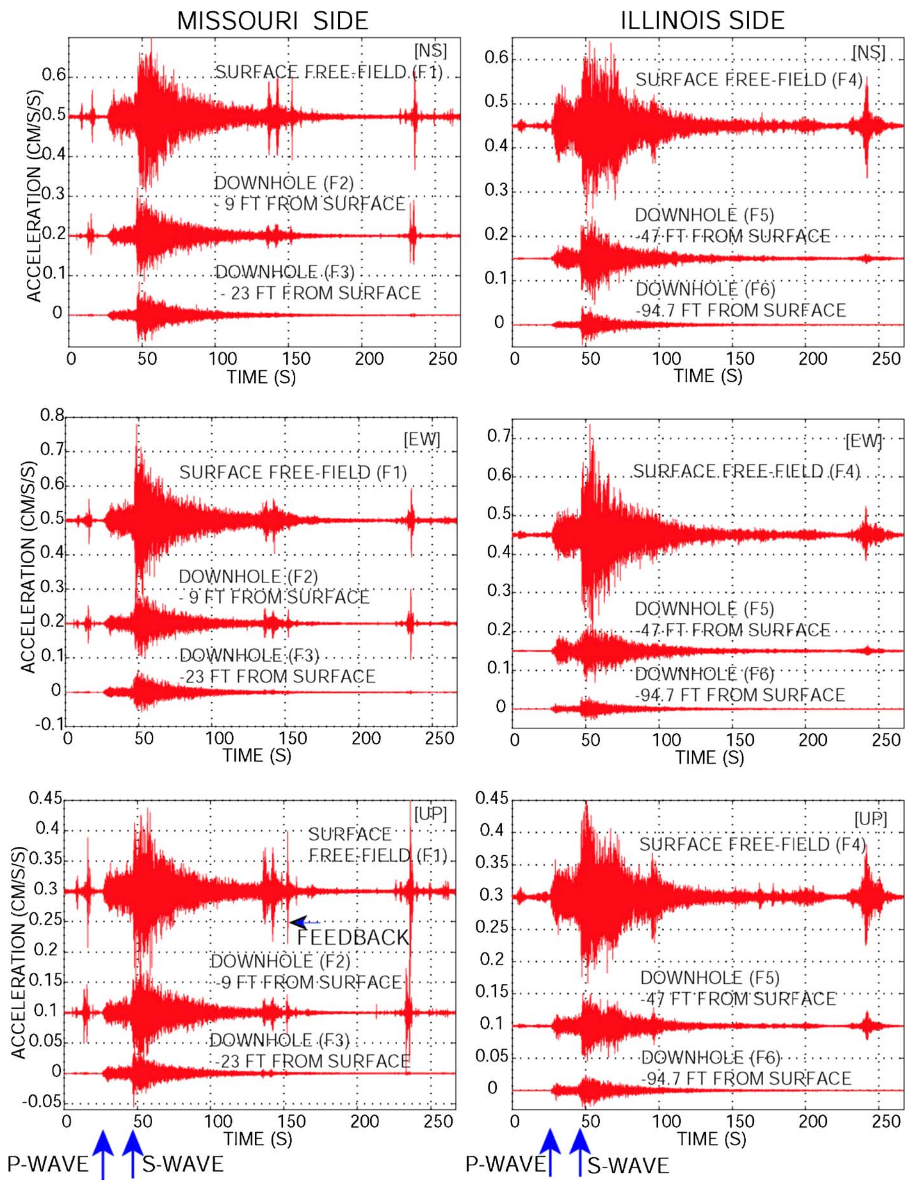

Figure 4. 267 seconds of free-field (NS, EW, and vertical) acceleration data from surface and downhole deployments at both Missouri and Illinois sides. The earthquake of 1 May 2005 is best identified by the lower downhole accelerometers as they are the least affected by site response effects clearly seen at surface, and also by ambient vibration effects from the bridge reflected back to the surface and mid-downhole accelerometer locations. Short-duration spikes or bursts of energy, such as those preceding the P wave from the earthquake are likely due to traffic on the bridge.

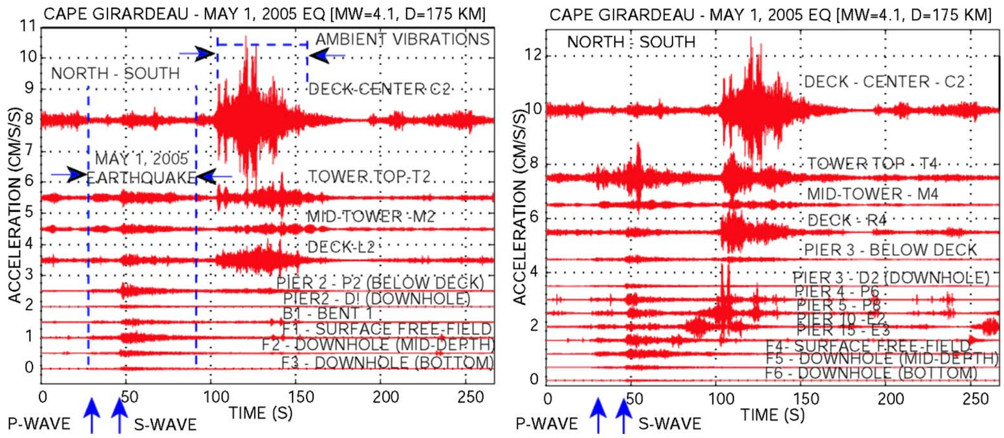

Figure 5. The (NS) motions at free-field locations are shown relative to the piers and deck center and top of towers. The amplified motions of the structure between 100 and 150 seconds into the record are anomalies caused by cable vibrations of the structure and not by the much smaller earthquake motions between 30 and 100 seconds into the record.

celerometers (F2 and F5) and of surface accelerometers (F1 and F4) are significantly amplified when compared to the motions at the lowest downhole accelerometer locations (F3 and F6). The motions at surface and middle downhole locations are also affected by ambient motions of the bridge when compared to the motions at the lowest downhole accelerometer locations.

- When compared with the low-amplitude earthquake motions, the feedback from the bridge ambient motions (seen as spikes) are significant to the degree that their amplitudes are similar to the response caused by this earthquake. Such spikes are observed several times in the 267-second-long record. These feedback motions are higher at surface and attenuate as they travel to the middle and lowest downhole.
- Using the approximately 78 seconds of the earthquake portion of the 267-second length of the data (approximately between 30 and 110 seconds), it is possible, as shown later in the paper, to infer qualitative and quantitative site amplification that occurs at the free-field locations (even from such small amplitude motions caused by the distant small earthquake).
- Also later in this paper, this long-duration data that contains earthquake record of 1 May 2005 will be compared to another, similarly long-duration data that does not contain earthquake data.

Motions in the Lateral (NS) Direction

Figure 5 shows NS time-history plots of motions at the center of the deck (C2), tower tops (T2 and T4), mid-tower locations (M2 and M4), side-span deck (L2 and R6),

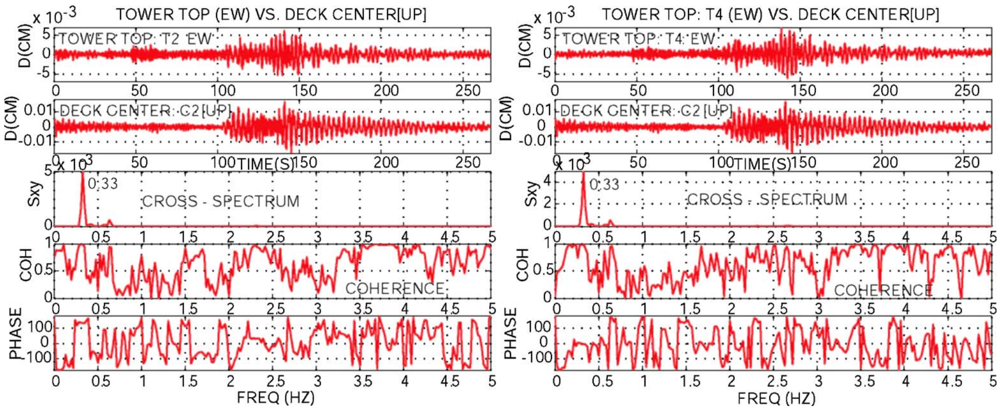

Figure 6. Displacement time histories, cross-spectrum, coherency, and phase-angle plots: (a) EW motions between Tower Top at Pier 2 (Location T2) and vertical motions at center of deck, and (b) EW motions between Tower Top at Pier 3 (Location T4) and vertical motions at center of deck.

and other pier locations, and the free-field arrays. Compared to the ambient motions at deck center and other key structural locations (C2, T2, T4, L2, and R6), the free-field motions due to the 1 May 2005 earthquake are much smaller.

Coherency of Tower Longitudinal (EW) and Deck Center (UP) Motions

These records reveal some important behavior of the deck and tower tops, which are connected by cables under tension. Figure 6 shows displacement time histories in the EW (longitudinal) direction of the bridge at the north end of tower top locations (T2 at Pier 2 and T4 at Pier 3) and the north end deck center location, C2. At approximately 0.33 Hz, vertical motions at C2 and EW motions at T2 are highly coherent and approximately 180° out of phase, while vertical motions at C2 and EW motions at T4 are highly coherent but are in phase (0° phase angle), indicating that while deck center is going up, T4 is in phase and therefore moving eastward, while T2 is 180° out of phase and therefore moving westward. Figure 7 shows similar plots for the east-west motions at T2 and T4 that are perfectly coherent and (180°) out of phase at 0.33 Hz. Furthermore, the plots in Figure 8 show evidence that the north and south ends of the center of the deck are not vibrating perfectly in phase even though there is perfect coherency between the two. As demonstrated in more detail in Figure 9, the north and south ends of the deck center are not in phase, whereas T2 and T4 are 180° out of phase. This implies that the amplified ambient motions of key locations of the structure (deck center, top of towers) are most likely due to time-variant cable action—that is, stored tensile energy in the cables vary and increase/decrease according to the displacements of the deck center and tower tops (as well as other locations where cables connect the deck to the towers). However, it is uncertain whether all cables on either north end or south end, and in particular those that are symmetrical with respect to the center of the deck, remain in proportion-

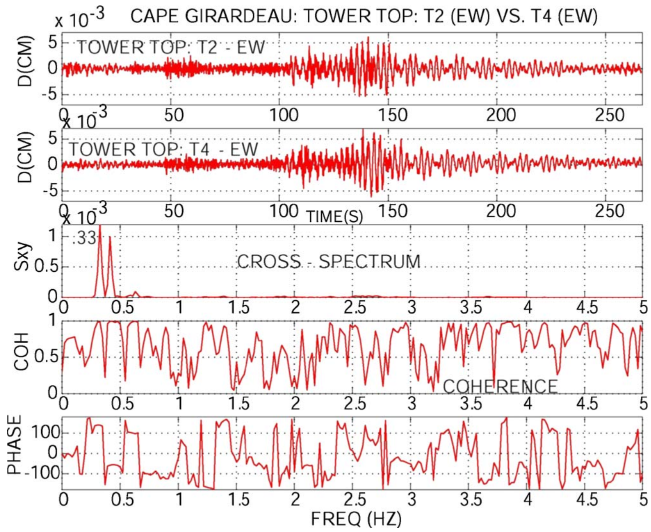

Figure 7. Displacement time histories, cross-spectrum, coherency, and phase-angle plots of EW motions between Tower Top at Pier 2 (Location T2) and Tower Top at Pier 3 (Location T4).

ally compatible tension. Thus the cables may continuously store and release varyingly differential energy. The amplified motions of the deck and tower tops may be caused by such cable actions.

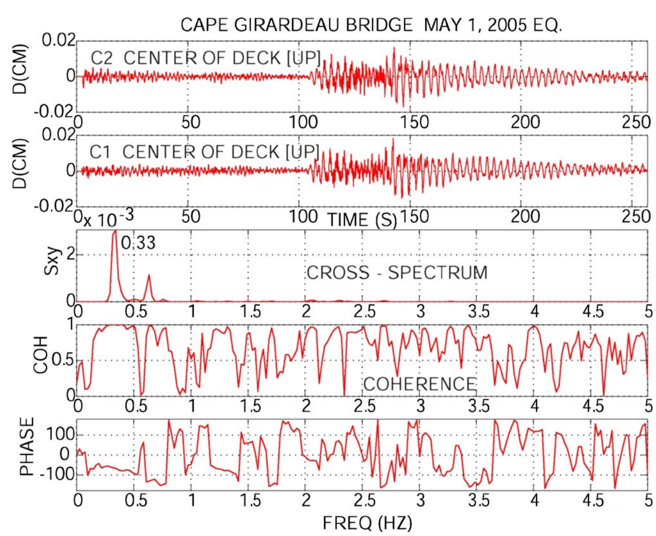

Figure 8. Displacement time histories, cross-spectrum, coherency, and phase-angle plots of vertical motions at the north end (C2) and south end (C1) of the center of the deck.

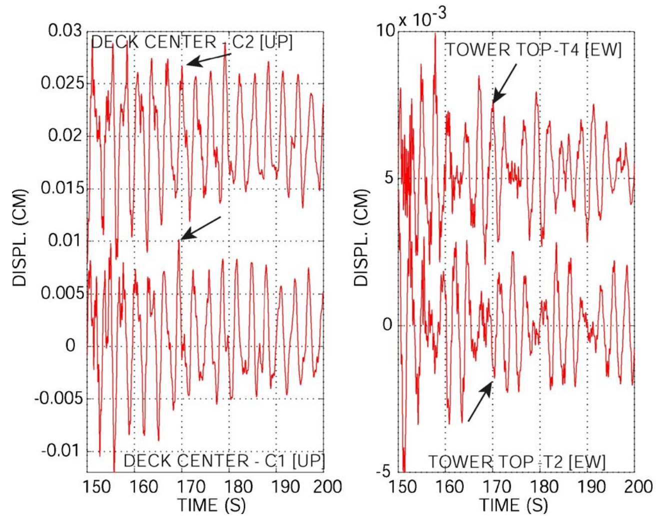

Figure 9. (a) Phase lag in vertical displacements of deck center north (C2) and south (C1) end locations, and (b) 180° out of phase of EW (longitudinal) displacements of tower top locations T2 and T4.

Relative Amplitudes of Windowed Data and Fundamental Vertical Frequency

Figure 10 shows vertical acceleration time history at deck center (C2) and its amplitude spectra for (a) total 267-s record, (b) windowed motion for 40 seconds mostly due to earthquake response, and (c) 60 seconds of amplified ambient record. With amplitude spectrum during earthquake about 10% of that during the amplified ambient motions, the figure exhibits that regardless of the low-amplitude level of shaking, several frequencies of the bridge are identifiable. While a mode at a particular frequency is not identified from the analyses of the low-amplitude data recorded, it is noted that the fundamental vertical mode of the bridge is approximately 0.33 Hz (3.0 s)—similar to the 0.29 Hz (0.34 s) frequency (period) computed by modal analyses performed both for the design (S. Hague, written comm., 2005) and by Dyke (2001) and Dyke et al. (2003).

DATA SET 2: 300-SECOND-DURATION RECORD WITHOUT AN EARTHQUAKE

As previously stated, one of the advantages in having continuous monitoring and streaming of data with broadband instruments is that recurring unusual responses and anomalies can be observed and interpreted, and if necessary steps can be initiated to eliminate or decrease their impact on the behavior of the structure. Due to the observance of non-earthquake-related amplified motions in Data Set 1, similar occurrences were searched in hours of data immediately before the earthquake of 1 May 2005. This was to check if such occurrences do randomly take place in the absence of earthquakes. One such case, identified in a ~300-second-long interval approximately six hours before the earthquake of 1 May 2005, was extracted from the archived data. Figure 11 shows a plot of this data from key locations of the bridge and also of the free-field lo-

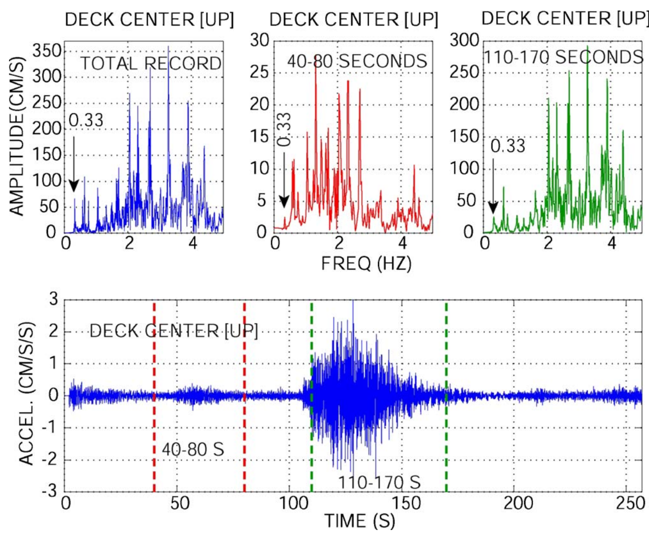

Figure 10. Acceleration time history of vertical motions at deck center (C2) (bottom) and amplitude spectra of total 267-second record, 40-second record (mostly due to earthquake response), and 60 seconds of amplified record (top).

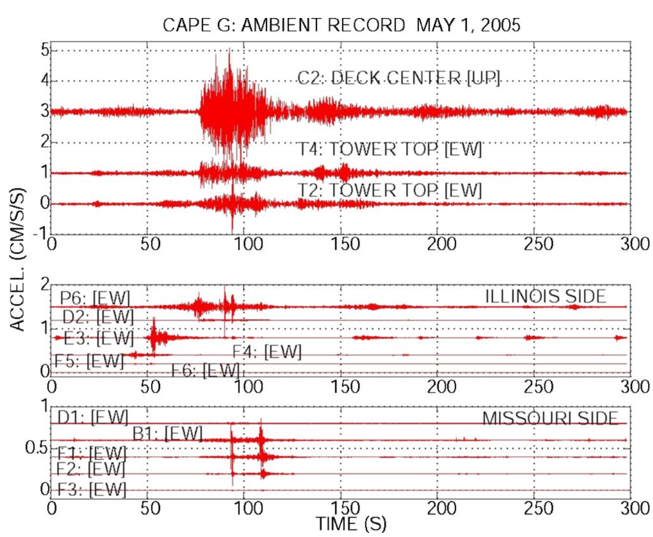

Figure 11. Data from approximately six hours before the occurrence of the 1 May 2005 earthquake exhibits amplified motions of the deck and also feedback to the MO side free-field array. Note the absence of significant motions on the deepest borehole sensor (F3).

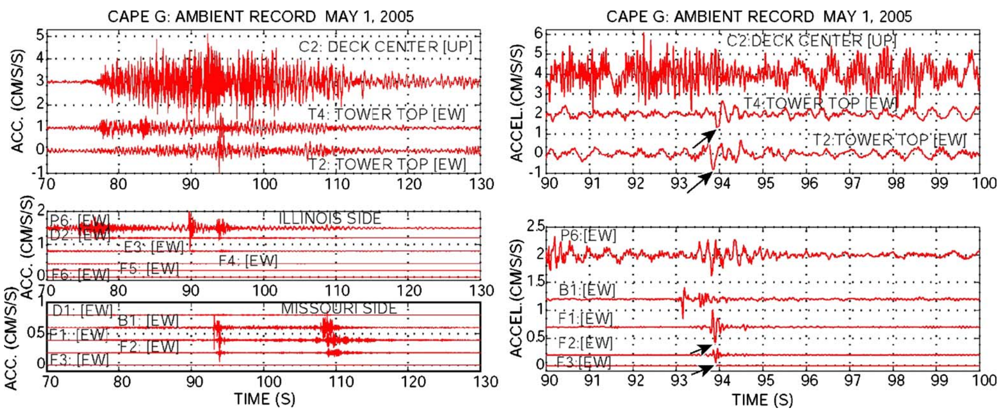

Figure 12. (a) 70–130 second and (b) 90–100 second windows of the ~300-second data exhibits motions from the bridge traveling to the free-field. The approximately 0.5-second period (2 Hz) waveforms superimposed by approximately 0.1-second period (10 Hz) waveforms are clearly apparent and are likely caused by cable vibrations.

cations on both the MO and IL sides of the bridge. Other occurrences of such amplified vibrations of the deck and towers are frequently observed in the continuously streaming data.

Although there is yet no systematic study of recurrent random amplified ambient motions, a logical explanation of such random and irregular fluctuations in duration and amplitudes of motions of the deck and towers of the bridge is that they are likely caused by cable vibrations—particularly because the vertical motion of the deck center and the EW (longitudinal) motion of the towers are coherent and are in-phase for significant structural frequencies (Figure 12). Also noted in Figure 12 is that some of the motions that originate at the bridge deck and tower are reflected to the piers and bents and then to the free-field sites—the reverse of that of an earthquake (e.g., motions starting at tower and deck travel to Bent 1, then to F1, and then to F2, and are attenuated and possibly diminished by the time they reach the lower downhole, F3). In other words, the structure is forcing the ground into motion.

The frequency at 2 Hz observed in the time-history plots of accelerations at deck center and tower tops are considerably different from the 0.33 Hz frequency previously noted as belonging to the fundamental vertical mode of the structure and is likely that of higher vertical mode.

The ambient motions of the bridge deck and towers exhibit several dominant frequencies, as depicted in the amplitude spectra in Figure 13 (plotted for both 0–20 Hz and 0–5 Hz frequency bands). It is seen in the figure that the NS spectra of tower top T2 location (at Pier 2) and T4 (at pier 3) are very similar. The same is true for the EW spectra. The 0.33 Hz frequency is observed in the EW spectra of the tower tops T2 and T4 as also in the vertical motions of the deck center C2, but is practically absent in the

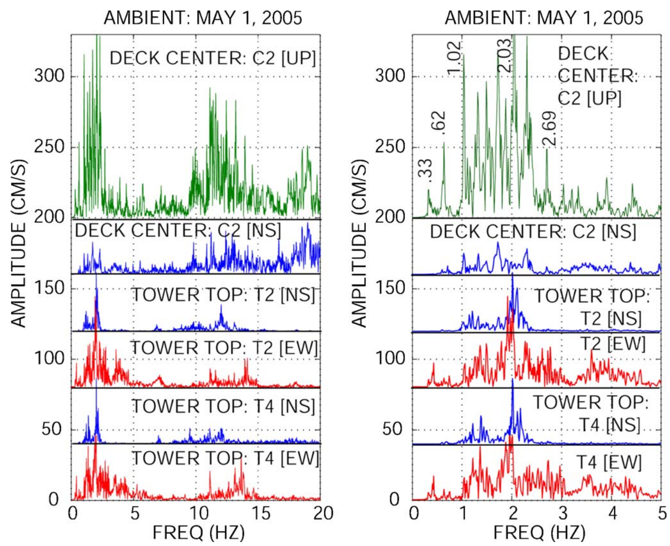

Figure 13. Amplitude spectra of ambient motions show that the frequencies of the motions of the two towers are similar. The deck center vertical motions and EW components of towers exhibit several frequencies that are also similar. The right figure is an expanded view of the 0–5 Hz range of the one on the left.

NS motions. While several frequencies are identifiable in the spectra, the different modes corresponding to the frequencies are not investigated herein.

DATA SET 3: EARTHQUAKE DATA OF 1 MAY 2005

1 May 2005 earthquake data (herein Data Set 3) of 78 seconds duration is extracted from Data Set 1 for further analyses.

Lateral (NS) Motions

Figure 14 shows the time histories and corresponding amplitude spectra of the NS motions west of deck center, and Figure 15 shows the similar data from east of deck center. In both figures, it is seen that the significant frequencies associated with both towers are identical, and that dominant peaks are around 1 and 2.2 Hz. Side spans (L2 and R6) and towers (T2 and T4) and mid-towers (M2 and M4) have significant energy between 2 and 2.3 Hz. Deck center displays several peaks, the lowest at 0.75 Hz.

Longitudinal (EW) Motions

Figure 16 shows the time histories and corresponding amplitude spectra of the EW motions at west of deck center, and Figure 17 shows data from east of deck center. The tower locations T2 and M2 (tower top and mid-tower at north end of Pier 2) and locations T4 and M4 (tower top and mid-tower at north end of Pier 3) exhibit significant peaks between 1.8 and 2.0 Hz and other significant peaks between 2.65 and 3.0 Hz. Al-

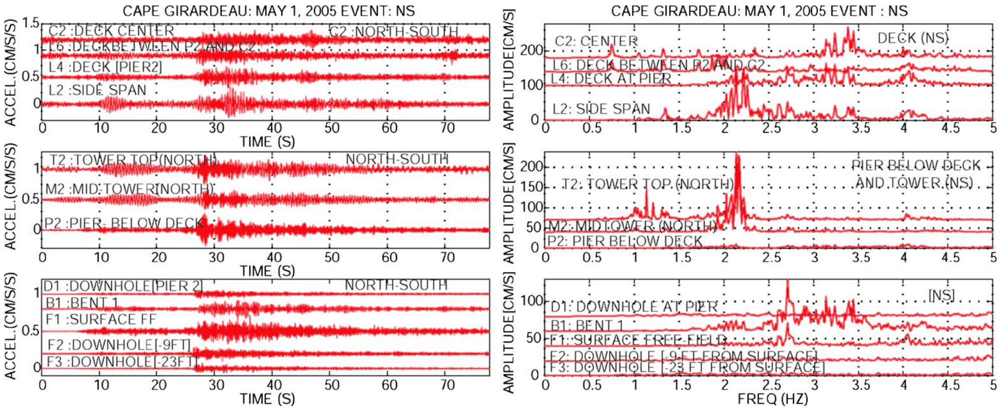

Figure 14. Time-history plots (left) and corresponding amplitude spectra (right) of the NS accelerations at key locations to the west of the deck center recorded during the 1 May 2005 earthquake.

though the significant frequency bands are similar for the towers at the two piers, their spectral shapes are not identical. For example, at T2 location, there is one clear peak around 2.1–2.2 Hz and a less dominant peak around 1.0–1.2 Hz, whereas there is only dominant peak around 2.1–2.2 Hz at T4 location. It is noted in Figure 17 that relatively large amplitude ambient motion, possibly caused by traffic or other means, is recorded/superimposed on the EW earthquake response of Pier 15 (approximately at 55 seconds of this plot). Since the spectral shapes of the three components are similar, it is likely that spectral characteristics of the ambient motion are similar to that caused by the earth-

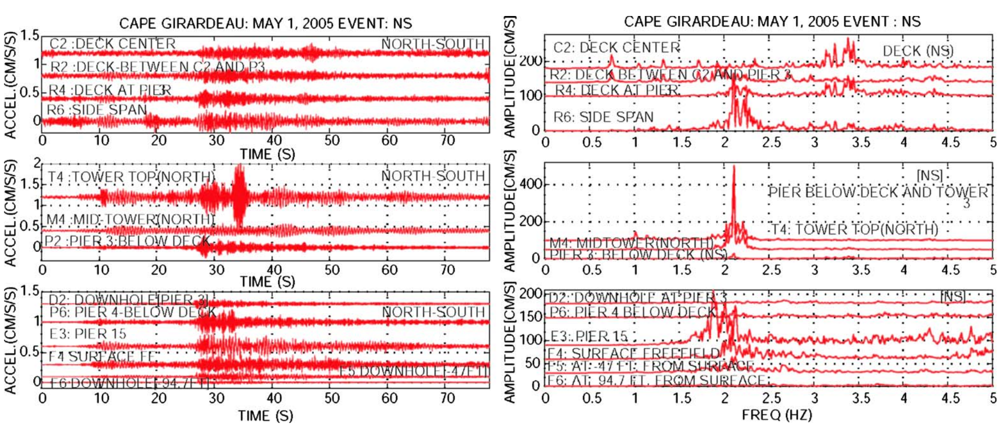

Figure 15. Time-history plots (left) and corresponding amplitude spectra (right) of the NS accelerations at key locations to the east of the deck center recorded during the 1 May 2005 earthquake.

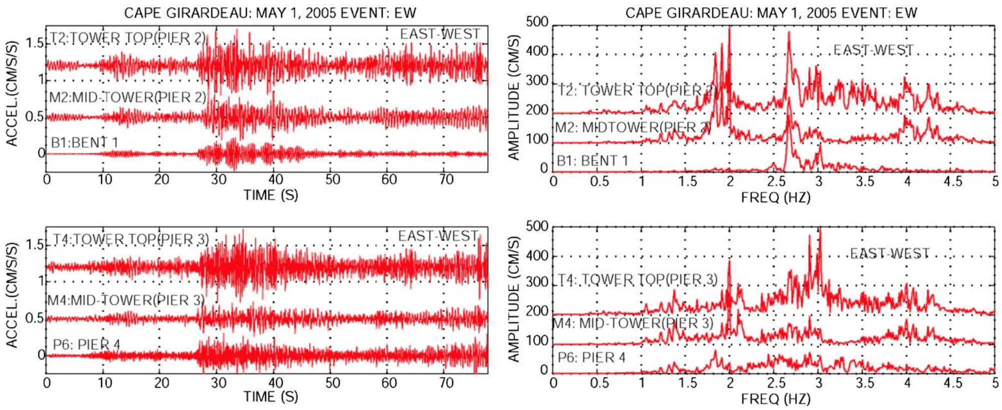

Figure 16. Time-history plots (left) and corresponding amplitude spectra (right) of the EW accelerations at bent 1, mid-tower and tower top at Pier 2, and at Pier 4 (location P6) and mid-tower and tower top of Pier 3 recorded during the 1 May 2005 earthquake.

quake (similarly as in Figure 10). Furthermore, it is noted in Figure 16 that at about 55 seconds and onward, tower (T2 and T4) and Pier 4 (P6) motions are also amplified possibly due to the amplified motion at Pier 15.

Vertical (UP) Motions

Figure 18 shows vertical accelerations (left) and corresponding amplitude spectra (right) at various deck locations, downhole at Pier 2, at Bent 1 and at the surface and free-field array to the west of deck center. Figure 19 shows vertical accelerations at vari-

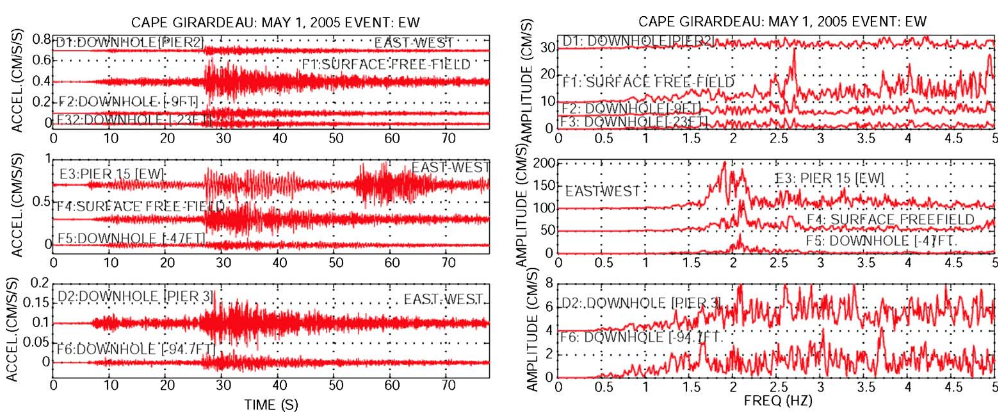

Figure 17. Time-history plots (left) and corresponding amplitude spectra (right) of the EW accelerations at deck center and key locations to the west of the center recorded during the 1 May 2005 earthquake.

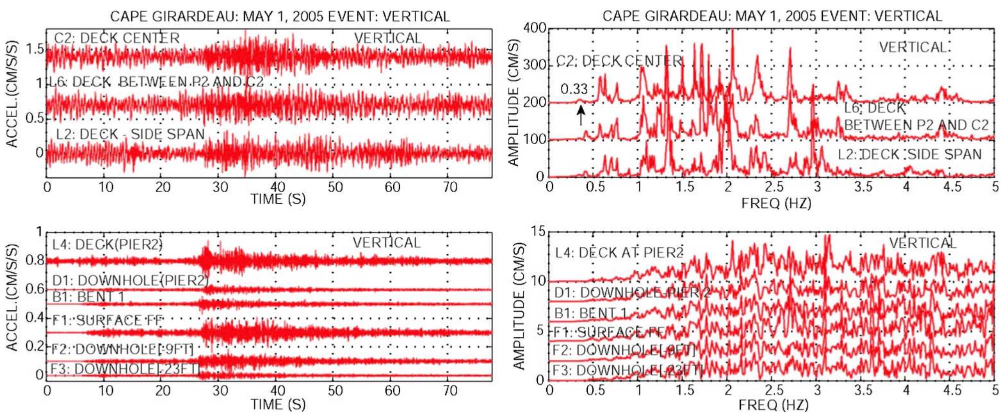

Figure 18. Time-history plots (left) and corresponding amplitude spectra (right) of the vertical accelerations at various deck locations, downhole at Pier 2, Bent 1, and surface and free-field array to the west of deck center recorded during the 1 May 2005 earthquake.

ous deck locations, downhole at Pier 3, Pier 15, and surface and free-field array to the east of deck center and corresponding amplitude spectra. There is a much richer set of modes displayed in the amplitude spectra of the vertical motions at different locations of the deck. The lowest frequency of the deck vertical motions is displayed at ~0.33 Hz. The ambient motion seen in the EW response recorded at Pier 15 is again noted in Figure 19. The amplitude spectra and associated frequencies of the motions at the nonstructural locations (free-field including downholes) and support locations of the structure (e.g., B1, L4, R4, D1) to the west of deck center are very similar but are considerably

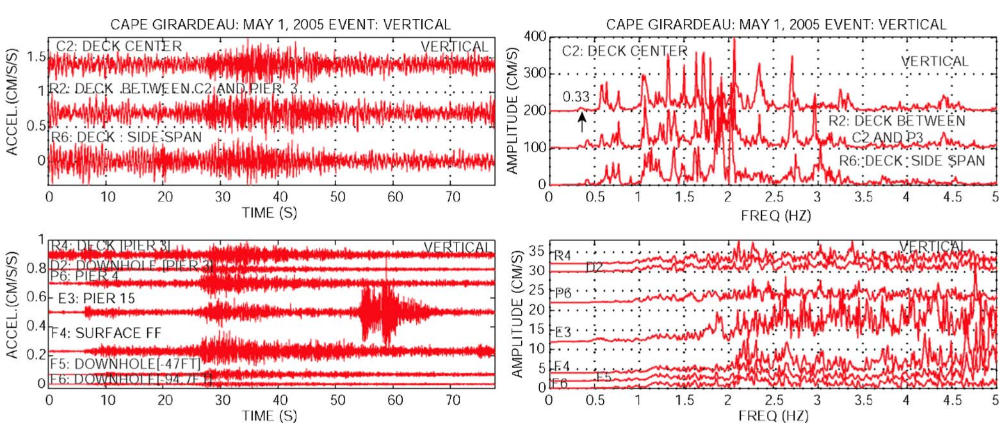

Figure 19. Time-history plots (left) and corresponding amplitude spectra (right) of the vertical accelerations at various deck locations, downhole at Pier 3, Pier 15, and surface and free-field array to the east of deck center) recorded during the 1 May 2005 earthquake.

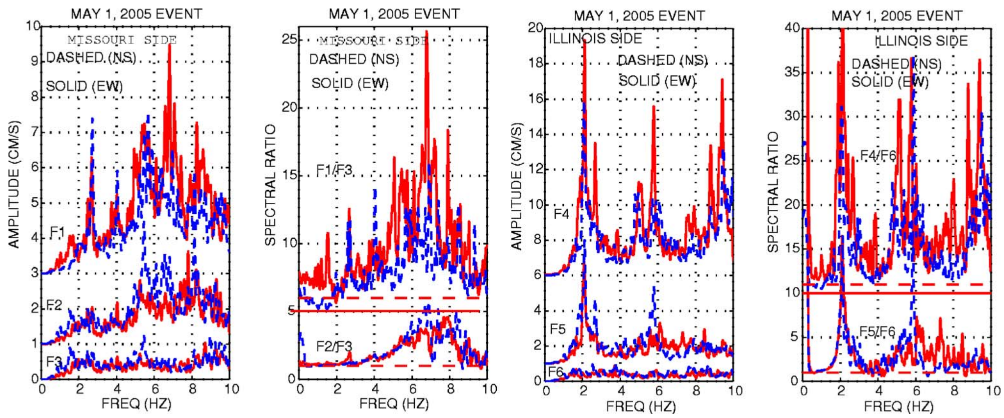

Figure 20. Amplitude spectra and spectral ratios of the free-field surface and downhole (EW) motions at the MO and IL sides clearly show site amplifications at 2.5 and 6 Hz on MO side and at 2 and 6 Hz on IL side.

different than the spectra and frequencies of the motions at the nonstructural locations (free-field and downholes) and support locations (Pier 15, Pier 3, Pier 4, Pier 5, downhole at Pier 3). As discussed later, this is attributed to different site conditions (different shear-wave velocities and depths to hard soil) at the (MO) west side versus the (IL) east side of the bridge.

Site Response Evaluated from Free-field Arrays

Limited site response computations are presented herein to provide insight on site effects at each end of the bridge. Amplitude spectra of EW motions at both Missouri and Illinois surface and downhole locations are shown in Figure 20. Also shown in the figure are the spectral ratios for each side (Missouri or Illinois) of motions at the surface and mid-depth downhole locations with respect to the downhole location at the bottom. Spectral ratios indicate clear dominant frequencies (periods) at 1.8 and 2.5 Hz (0.40 and 0.55 s) for the west end and 2.0 Hz (0.5 s) for the east end. Higher frequencies (periods) between 5.5 and 6.5 Hz (0.15 and 0.18 s) are also dominant on both ends.

CONCLUSIONS AND RECOMMENDATIONS

In this paper, a new, integrated network of broadband seismic instruments deployed on and in the vicinity of the new cable-stayed bridge in Cape Girardeau, Missouri, is introduced. This is a significant accomplishment providing opportunities to acquire high-quality data even at small amplitudes in the order of 10^{-4}–10^{-3} g. The network has many unique features:

- There is a structural array comprising an extensive set of accelerometers deployed at the foundations, piers, deck, and towers of the superstructure,

- There are two free-field arrays, one on each side of the Mississippi River. Each free-field array comprises a triaxial surface and two triaxial downhole accelerometers.
- Signals from all of the accelerometers of the integrated array are recorded in real time at a central recording station at the site.
- Signals are transmitted to the IRIS data center from where it is accessible to the user community. Remote real-time recording and communication capability are achieved. Users of the data can get direct access to the real-time streamed data.
- Continuously streamed data is temporarily stored for several weeks and earthquake records are processed and stored indefinitely. Temporary storage of data provides an opportunity to be able to retrieve data recorded in the past.
- The monitoring system provides an advantage in that its functionality can be checked remotely.

Although the instrumentation system is intended for recording responses of the structure to moderate-to-large seismic events, it can, as demonstrated, also record low-amplitude motions, wind- and traffic-induced motions, and motions caused by tower-cable-deck interactions. Continuously recorded low-amplitude data can facilitate different types of studies to assess and predict the performance of the structure during stronger shaking events. Such low-amplitude motions can be used in assessment of dynamic characteristics of the structure and provide a basis for estimating levels of shaking during much less frequent stronger events (as is the case for the New Madrid Seismic Zone).

Preliminary analyses of low-amplitude data including an earthquake demonstrates that (1) the data is of high quality as indicated by strong signals necessary in identification of response characteristics, and (2) observation and identification of unusual ambient vibrations that take place. While there appear to be significant ambient vibrations caused by tower-cable-deck interactions, their amplitudes are very small compared to amplitudes that may be experienced by stronger shaking. However, in the long term, data from these small-amplitude vibrations provide opportunities to study cable rupture scenarios, material fatigue, and low-cycle fatigue.

The data at low amplitudes are so good that feedback of ambient vibrations originating at the structure and traveling to the surface and downholes are observed in detail. Thus it is clearly seen that the structure moves the ground during stronger (but still low-amplitude) ambient vibrations caused by towers-cable-deck interactions.

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 or liquefaction or wind-related) can be integrated into the new system.

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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. However, since the installation of the monitoring system, data management became a very serious issue. Here, the author specially thanks Tim Ahern, manager of Data Management Systems at IRIS and Chris Stephens, manager of Data Center of NSMP at USGS, Menlo Park, CA. Both contributed to the facilitation of data management and subsequent processing of the data that is continuously streaming from the Cape Girardeau Bridge seismic monitoring network.

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