

INTEGRATED SITE AND STRUCTURAL SEISMIC INSTRUMENTATION ARRAYS FOR A CABLE-STAYED BRIDGE – RECORDINGS AND ANALYSES

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ABSTRACT

The cable-stayed New Cape Girardeau (MO) Bridge is approximately 80 km from the epicentral region of the 1811–1812 New Madrid earthquakes. It is designed for the possibility of a magnitude 7.5 or greater earthquake. The seismic instrumentation system integrates sub-arrays on the superstructure (towers and deck), pier foundations, and two free-field arrays, one on each side near the 1206 m span of the bridge. The 84-channel system records and streams data at the site, transmits and broadcasts synchronized real-time signals from combinations of uniaxial and tri-axial accelerometers via the internet. Each of the two free-field arrays comprises three (one surface and two downhole) tri-axial accelerometers. Ambient vibrations and recordings of a Mw=4.1 earthquake at an epicentral distance of 175 km from the bridge are analyzed to infer structural and site response characteristics of the bridge. The data depicts unique dynamic characteristics of the soil-structure system and the traveling of the seismic waves from downhole through the foundations to the superstructure. The interaction of the cables define the response of the deck and towers and in turn generate ambient vibrations that force the ground as clearly depicted by the travel of the waves from the structure to the surface free-field and to the downhole. Site transfer functions computed using free-field site characterization data and spectral ratios using earthquake data identify reasonably comparable site frequencies.

Keywords: site array, site response, site characterization, ambient, earthquake motions

INTRODUCTION

The New Madrid area, where the great earthquakes of 1811–1812 occurred, is a highly 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 (here in after, the Cape Girardeau Bridge), in service since December 2003, is located approximately 80 km due north of New Madrid, Missouri. 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 a design response spectrum anchored to a zero-period acceleration of 0.36 g with a 10 % probability of being exceeded in 250 years (Woodward-Clyde, 1994). The Federal Highway Administration (FHWA), Missouri Department of Transportation (MoDOT), the Multi-disciplinary Center for Earthquake Engineering Research (MCEER), and the U.S. Geological Survey (USGS) collaborated in developing the seismic monitoring system for the new bridge.

The general schematic of the bridge, shown in Figure 1, illustrates (a) overall longitudinal dimensions of the bridge and key elevations, and (b) key sensor locations alongside the bridge.

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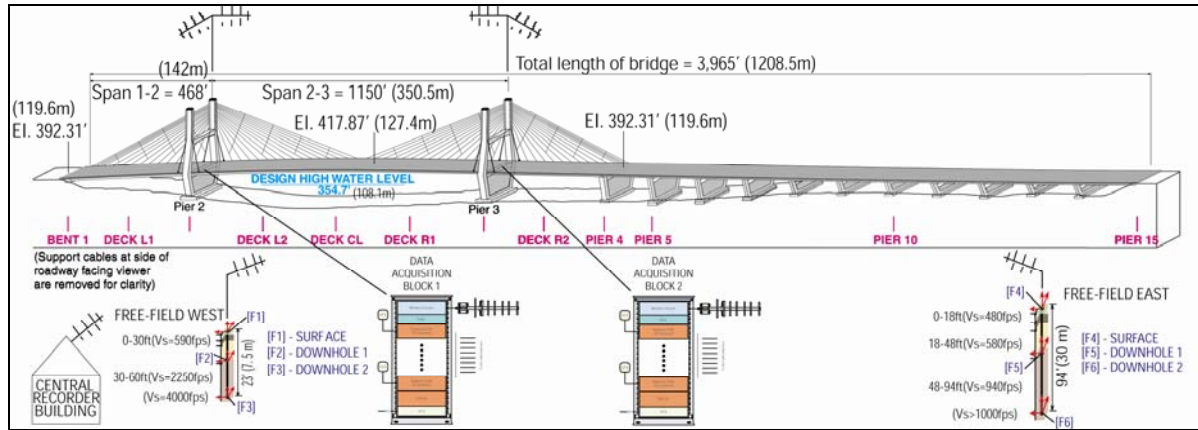


Figure 1. The figure illustrates (a) longitudinal dimensions and key elevations of the bridge, (b) general schematic of the seismic monitoring system with antennas for wireless communication of data between different locations to and from the Data Acquisition Blocks housed in Pier 2 and Pier 3 towers, and to the off-structure Central Recording System and (d) free-field arrays on both Missouri and Illinois sides. Shear wave velocities shown in fps. [1fps=0.3048m/s].

The objective of this paper is to introduce details of the extensive, state-of-the-art, real-time, broadband seismic monitoring network deployed on and in the vicinity of the new Cape Girardeau Bridge. The paper also presents preliminary analyses of low-amplitude data including motions at $\sim 10^{-4}$ – 10^{-3} g levels caused by a small earthquake that occurred 175 km away, and ambient vibrations caused by tower-cable-deck interactions, sources of which may be traffic or wind. For example, site response effects or soil-structure interaction or tracing of motions from the free-field to the top of tower or reverse phenomenon caused by excitations at the free-field from ambient vibrations of the structure (tower-cable-deck interaction) can be clearly observed. A variety of computations can be made to provide insight into vibrational behavior of the bridge. In this paper, sample analyses of data from the network are presented. Detailed analyses are provided elsewhere (Çelebi, 2006). Data streaming started in March 2005.

INSTRUMENTATION

The detailed schematic of the bridge in Figure 2 shows key locations and orientations of the 84 channels of accelerometers deployed on the bridge and the two free-field arrays. Identifier two-character location codes are important for data management and for referencing motions this paper. All horizontal sensors oriented transverse to the bridge are more closely aligned to NS, and longitudinal sensors are closely aligned to EW; hence, hereafter they referred to as NS and EW instead of lateral and longitudinal.

In addition to 84 channels of Kinemetrics EpiSensor¹ accelerometers, additional monitoring hardware consists of Q330¹ digitizers, and data concentrator and mass storage devices (Balers²) with wireless communication units (Figure 1). At each one of the hubs at Piers 2 and 3, combination of Q330 digitizers/recorder and Balers units constitute a multi-channel Data Acquisition Block (DAQ Block) that collects the analog signals from the accelerometers located throughout the bridge and then

¹ Citing commercial hardware throughout this manuscript does not imply endorsement of vendors or their products.

² Balers 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 Balers serves as the brain and router of the data acquisition system. Balers-14 works with a single Q330 unit. Balers45 works with multiple number of Q330 units. In the case of Cape Girardeau instrumentation scheme, since there are multiple Q330 units, only Balers45 units are used.

transmits the digitized data to the Central Recording System (CRS) using wireless radio transmittal via the antennas shown in Figure 1. The CRS merges the streamed data from the DAQs, records on site on a pre-planned manner using a trigger algorithm to produce file events and broadcasts the streamed data using standard TCP/IP communications protocol. From CRS, data are transmitted to Incorporated Research Institutions for Seismology (IRIS) for archiving and online dissemination to the user community.

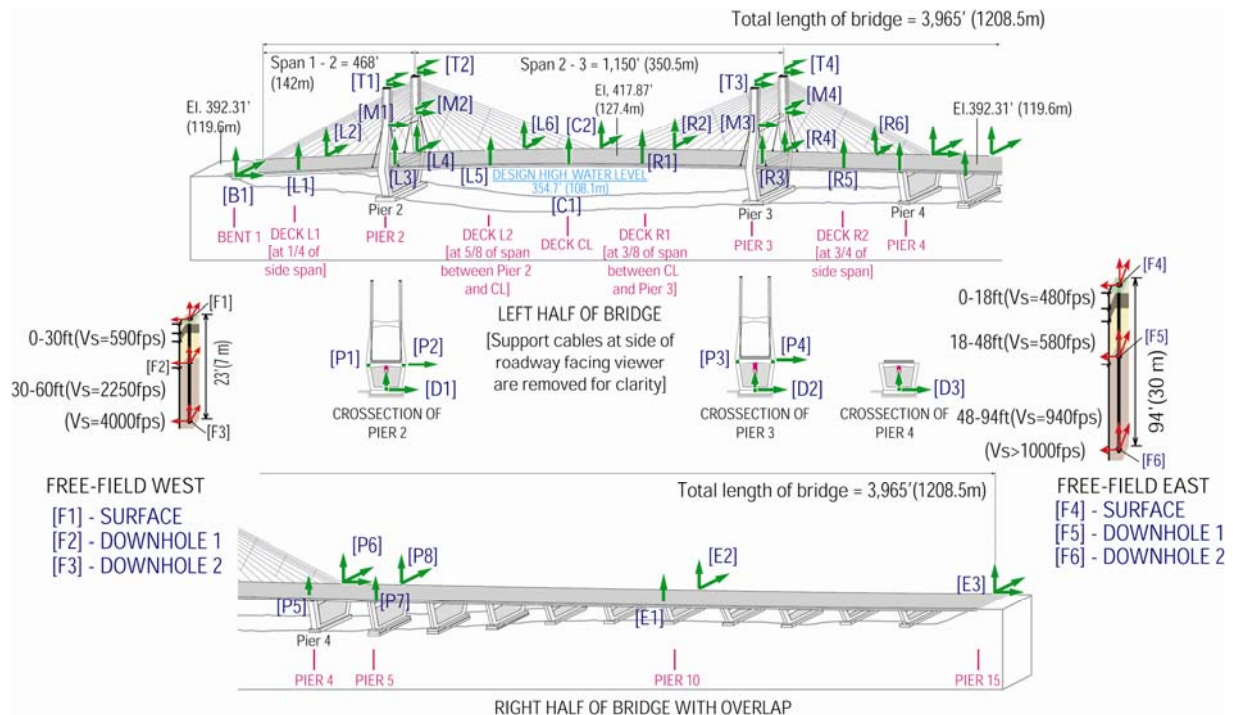


Figure 2. General schematic illustrating longitudinal dimensions of Cape Girardeau Bridge, and the locations and orientations of the accelerometers – both for the bridge and its piers and the free-field arrays on Missouri and Illinois sides. Location identifier codes (e.g. T1 for tower top location at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

Figure 2 also shows the general accelerometer deployment scheme for deck locations at the centerline (CL) and at L1, L2, R1 and R2, the exact locations of which are based on modal analyses (S. Dyke, written communication, 2001). 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; hence, there is a separate set of sensors at pier elevation 121.3 m (398 ft) (Figure 2).

One of the two permanent surface and downhole free-field arrays is deployed at the Missouri [MO] side and the second 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 300m (~900 ft) south-east of Pier 15 (Figures 1 and 2). Geotechnical characteristics of the boreholes that house the triaxial downhole accelerometers at defined depths from the surface are qualitatively and quantitatively shown in Figures 1 and 2. On the MO side, the two downhole accelerometers are at 9ft (~3m) and 23 ft. (~7.5m) from the surface. On the IL side, the two downhole accelerometers are at 47 ft (~14.3 m) and 94 ft. (~30m) from the surface. 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. Comparative computations of site transfer functions using borehole data and spectral ratios using earthquake data are provided later in the paper.

SAMPLE DATA ANALYSES

Sample analyses are performed for a 267-second interval of data that includes the M=4.1 earthquake that occurred at 12:37:32 (UTC) on May 1, 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). Detailed results are provided elsewhere (Çelebi, 2006).

Figure 3 shows the full 267 seconds of only the NS component of acceleration data from MO and IL free-field arrays. The length of the record represents neither the duration of the earthquake nor the strong shaking caused by the earthquake. Such long duration (~78 sec) shaking at this site from a small earthquake that occurred 175 km away is caused by crustal reverberations and surface waves (Hanks, 2005). The records are characterized by high signal to noise content even at small amplitudes ($\sim 10^{-4}$ of g levels). The earthquake related motions at locations of the middle downhole accelerometers (F2 and F5) and of surface accelerometers (F1 and F4) are significantly amplified when compared to the lowest downhole accelerometer locations (F3 and F6). On the other hand, the amplified and resonating ambient motions (exemplified by spikes or burst of energy) that originate at the structure are attenuated, as expected, as they travel back to surface and downhole locations.

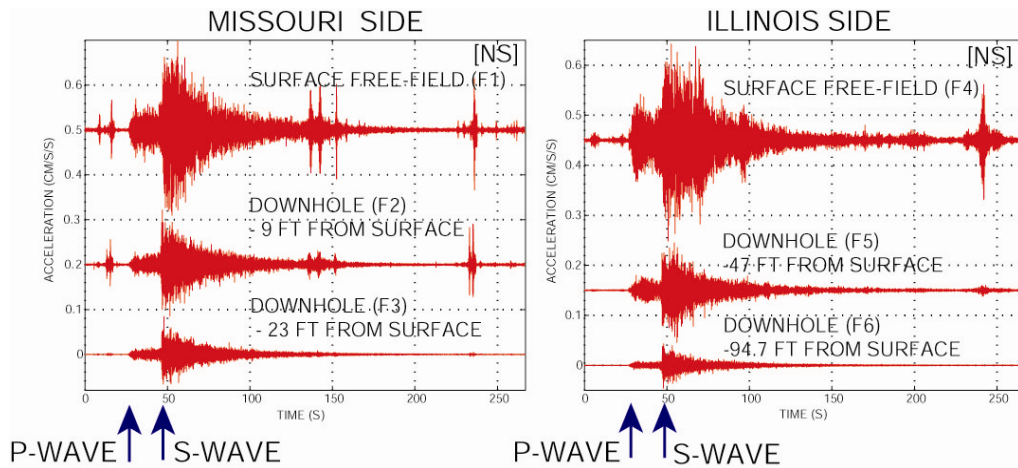


Figure 3. Accelerations (NS-267 sec) from surface and downhole free-field deployments at both Missouri and Illinois sides. May 1, 2005 earthquake is best identified by the lower downhole accelerometers as they are least affected by site response effects clearly seen at surface. Ambient vibration effects from the bridge are reflected back to the surface and middle downhole accelerometer locations. Short-duration spikes or bursts of energy are likely due to traffic on the bridge.

Figure 4 shows NS accelerations at center of the deck (C2), tower tops (T2 and T4) mid-tower locations (M2 and M4) side span deck (L2 and R6) 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, R6), the free-field motions due to earthquake are much smaller.

Further analyses of the record reveals some important behavior of the deck and tower tops, which are connected by cables under tension. Figures 5 shows displacement time histories (derived from double-integrated accelerations) 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 6 shows similar plots for the (a) east-west motions at T2 and T4 which are perfectly coherent and (180°) out of phase at 0.33 HZ and (b) north and south ends of deck center that are not vibrating perfectly in phase even though

there is perfect coherency between the two. This implies that the amplified ambient motions of key locations of the structure (deck center, top of towers) are possibly due to time-variant cable action – that is, tensile energy stored in the cables varies in time and increases/decreases according to the displacements of the deck center and tower tops. Similar behavior is expected to occur at 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 center of the deck, remain in proportionally compatible tension. Thus, the cables store and release energy continuously and thus frequently cause resonating amplified motions due to cable-deck-tower interaction. The fundamental vertical frequency of the bridge is approximately 0.33 Hz – similar to the 0.29 Hz frequency computed by modal analysis performed by Dyke (2001). Another example of frequently occurring amplified ambient motions caused by cable-deck-tower interactions as observed from the continuously streaming data is presented later in the paper.

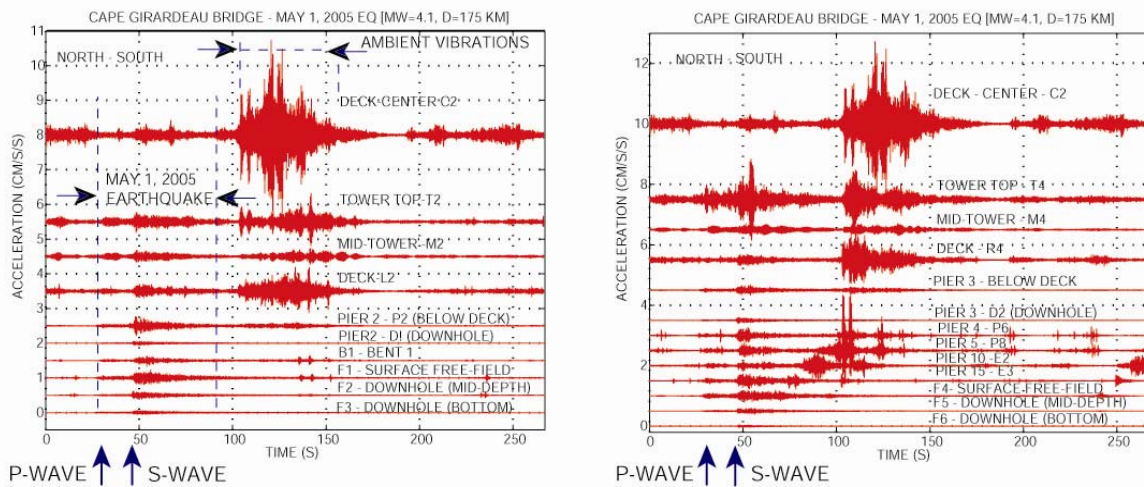


Figure 4. The (NS) motions at free-field locations are shown relative to the piers and deck center and top of towers. The amplified motions between 100-150 seconds are caused by cable-tower-deck interaction and resonance.

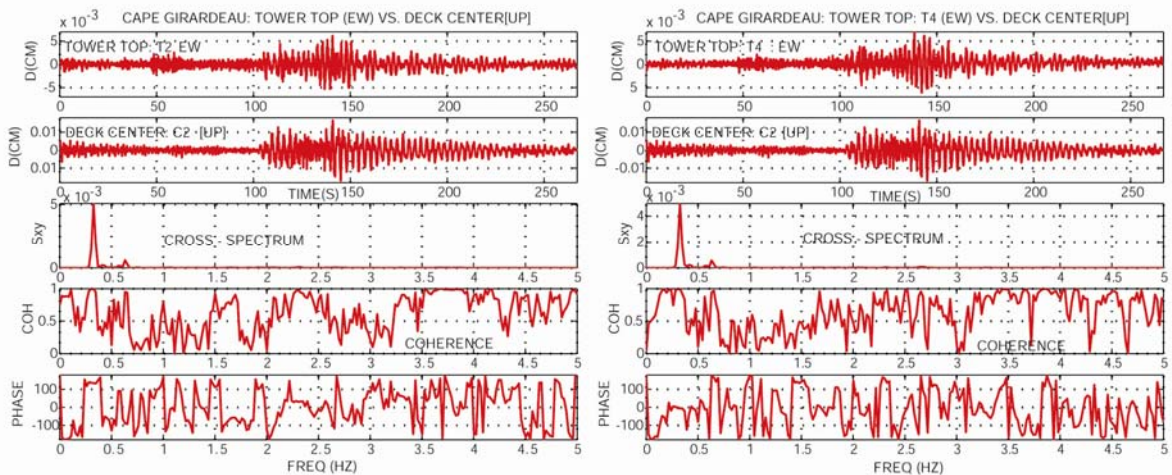


Figure 5. Displacement time-histories, cross-spectrum, coherency and phase-angle plots. [left]: EW motions between Tower Top (T2) at Pier 2 and vertical motions at center of deck, and [right]: EW motions between Tower Top (T4) at Pier 3 and vertical motions at center of deck.

To study the response of the bridge to the May 1, 2005 earthquake, a 78-second interval containing the signal is extracted from the 267 second data. Figure 7 shows the time-histories and corresponding

amplitude spectra of the NS motions at west of deck center. It is seen that the frequencies associated with the tower have significant peaks around 1 and 2.2 Hz. Side span L2 has significant energy between 2-2.3 Hz and also at 1.3 Hz. Deck center displays several peaks, the lowest at 0.75 Hz. Figure 8 shows the time-histories and corresponding amplitude spectra of the EW motions at west of deck center. The Pier 2 tower locations, T2 and M2, exhibit significant peaks between 1.8 and 2.0 Hz and other significant peaks between 2.65-3.0 Hz.

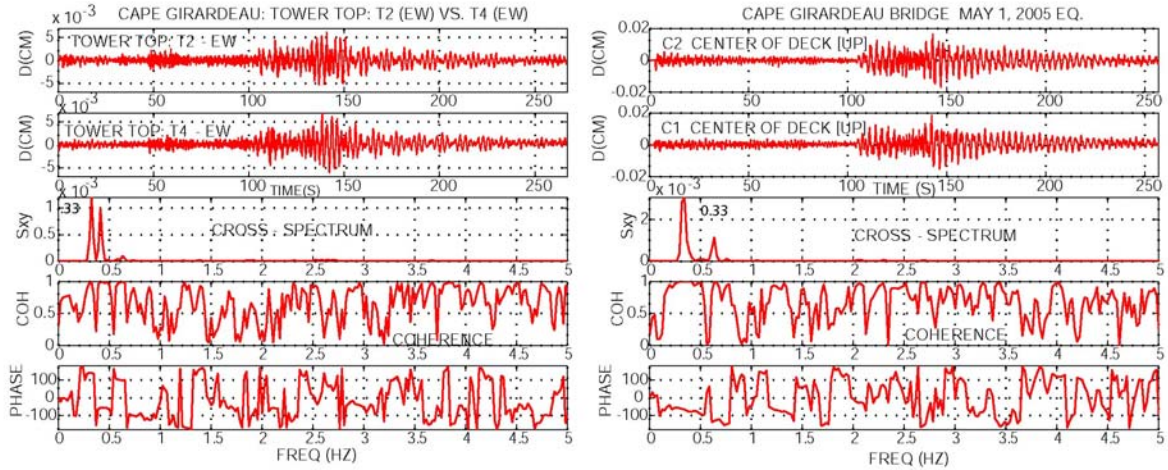


Figure 6. Displacement time-histories, cross-spectrum, coherency and phase-angle plots of (left) EW motions between Tower Top (T2) at Pier 2 and Tower Top (T4) at Pier 3 and (right) vertical motions at the north and south ends (C2, C1) of the center of the deck.

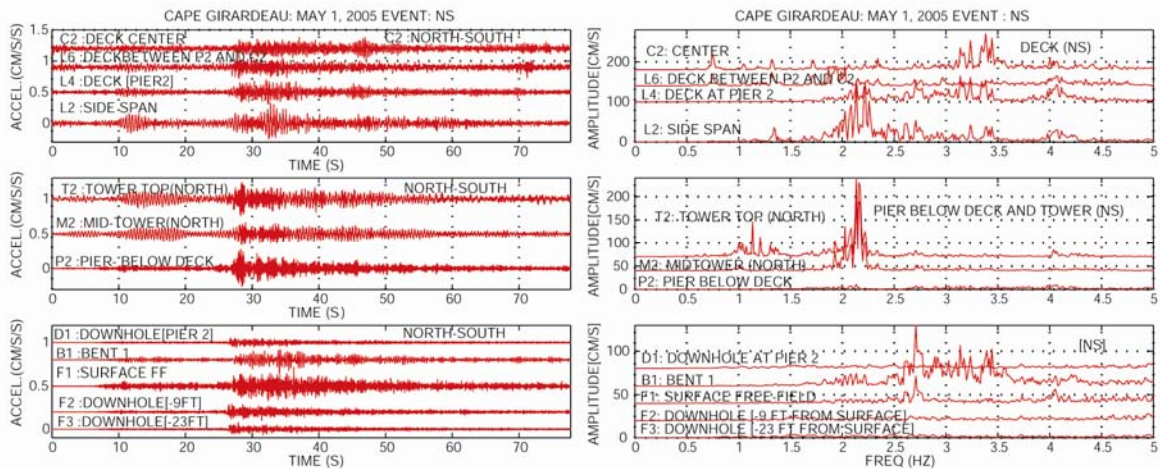


Figure 7. Time-history plots of the NS accelerations (left) and corresponding amplitude spectra (right), at key locations to the west of the deck center, recorded during the May 1, 2005 earthquake.

Figure 9 shows vertical accelerations and corresponding amplitude spectra at various deck locations, downhole at Pier 2, at Bent 1 and surface and free-field array to the west of deck center. Figure 10 shows vertical accelerations and corresponding amplitude spectra at various deck locations, downhole at Pier 3, Pier 15 and surface and free-field array to the east of deck center. Multiple sets of modes are displayed in The amplitude spectra display multiple modes at different locations of the deck. The lowest frequency of the deck vertical motions is evident at ~ 0.30 - 0.33 Hz. The amplitude spectra and associated frequencies of the motions at the non-structural 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 different than the spectra and frequencies of the motions at the non-structural

locations (free-field and downholes) and support locations (Pier 15, Pier 3, Pier 4, Pier 5, downhole at Pier 3). This is attributed to different site conditions (different shear wave velocities depths to hard soil) at the (MO) west side versus the (IL) east side of the bridge.

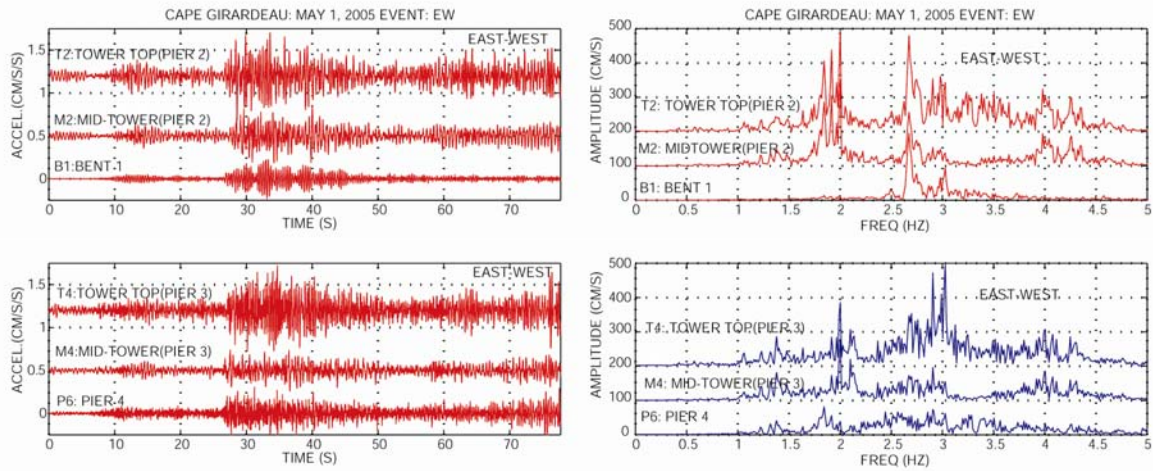


Figure 8. Time-history plots (left) and corresponding amplitude spectra (right) of the EW accelerations at bent 1, mid-tower and tower top at Pier 2, and at pier 4 [location P6] and mid-tower and tower top of Pier 3) recorded during the May 1, 2005 earthquake.

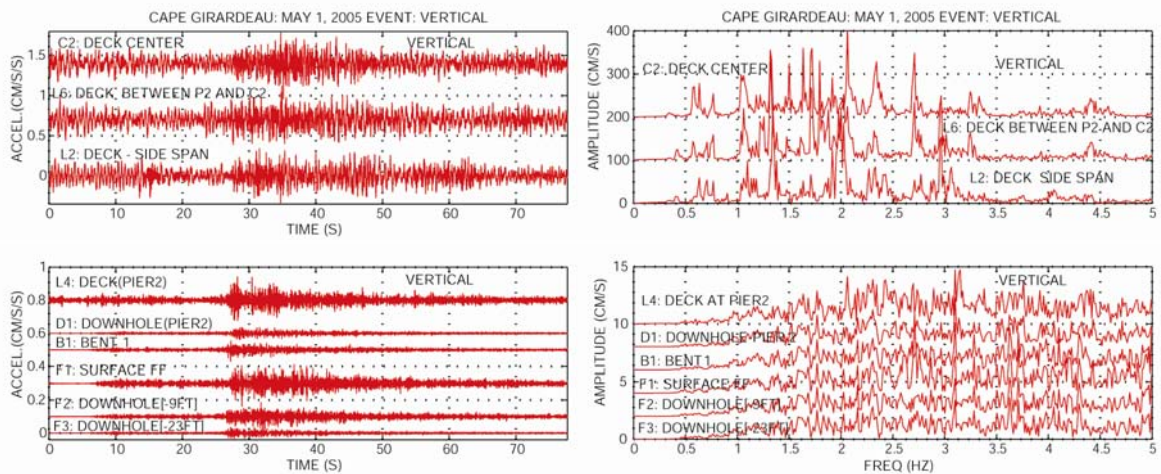


Figure 9. Time-history plots (left) and corresponding amplitude spectra (right) of the vertical accelerations at various deck locations, downhole at Pier 2, bent 1 and surface and free-field array to the west of deck center recorded during the May 1, 2005 earthquake.

One of the advantages in having continuous monitoring and streaming of data with broad-band instruments is that unusual responses can be observed, interpreted and, if necessary, steps can be initiated to diminish their impact on the dynamic behavior of the structure. Intervals of ambient vibrations like those presented above appear to be common. For example, as shown in Figure 11, within ~300 second-long interval approximately 6 hours before the May 1, 2005 earthquake, amplified ambient motions were found. In this case, as in the previous example, the vertical motion of the deck center and the EW (longitudinal) motion of the towers are coherent and are generally in-phase for significant structural frequencies. Also noted in Figure 11 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 – reverse to that of an earthquake (e.g. motions starting at tower and deck travel to Bent1, then to F1, and then to F2 and are attenuated and possibly diminishes by the time they reach the lower downhole, F3). In other words, vibrations of the structure are 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 than 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 10 Hz frequency superimposed on the 2 Hz motion is likely caused by cable vibrations.

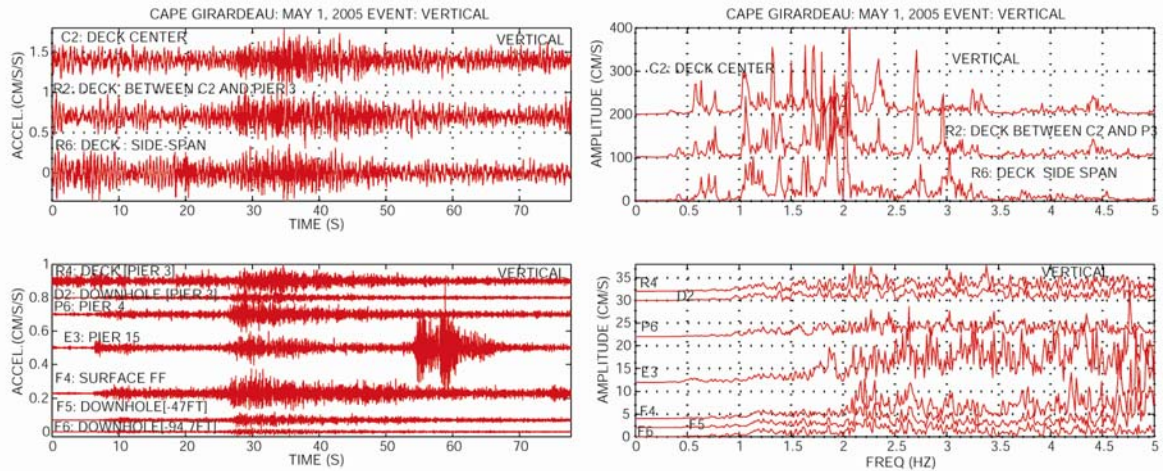


Figure 10. Time-history plots (left) and corresponding amplitude spectra (right) of the vertical accelerations at various deck locations, downhole at Pier 3, Pier 15 and surface and free-field array to the east of deck center recorded during the May 1, 2005 earthquake. Cause of amplified ambient motions at E3 unknown.

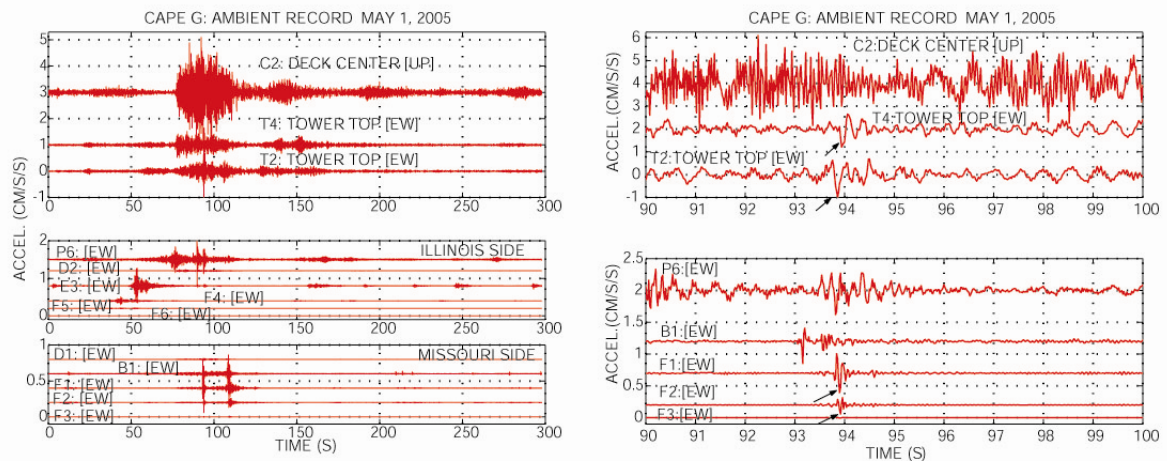


Figure 11. (Left) Data from approximately 6 hours before the occurrence of the May 1, 2005 earthquake exhibits amplified motions of the deck and also feedback to the MO side free-field array. (Right) 90-100 second window of the ~300 second data exhibits motions from the bridge traveling to the free-field. The 0.5 second (2 Hz) period waveforms superimposed by ~0.1 s period waveforms (10 Hz) are clearly apparent and are likely caused by cable vibrations. Note the near absence of significant motions on the deepest borehole sensor (F3).

The ambient motions of the bridge deck and towers exhibit several frequencies as depicted in the amplitude spectra in Figure 12 plotted for both 0-20 Hz and 0-5 Hz frequency bands. It is seen in the figures 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 spectra of NS motions.

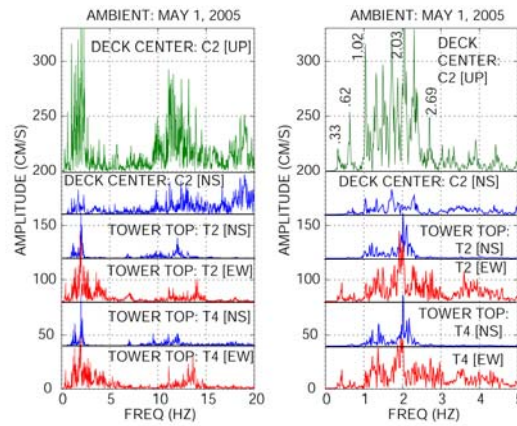


Figure 12. Amplitude spectra of ambient motions show that the frequencies of the motions of the two towers are similar and the deck center vertical motions and EW components of towers exhibit several frequencies that are similar.

SITE RESPONSE EVALUATED FROM BOREHOLE LOGS OF FREE-FIELD ARRAYS AND EARTHQUAKE DATA

Site response computations presented herein provide insight on site effects at each end of the bridge. Detailed depth-shear velocity profiles for both Missouri and Illinois free-field array sites and computed site transfer functions are provided in Figure 13. Although other methods are available, computation of site transfer functions is performed by using a software developed by Mueller (pers. comm., 1997) using Haskell's shear wave propagation method (Haskell, 1953, 1960). In this method, the transfer function is computed using linear propagation of vertically incident SH waves and as input data related to the layered media (number of layers, depth of each layer, corresponding shear wave velocities $[V_s]$, damping, and density), desired depth of computation of transfer function, sampling frequency, half space substratum shear wave velocity and density. Damping (ξ) in the software is provided as Q , a term used by geophysicists and is equivalent to damping by the relationship $\xi = 1/(2Q)$. Q values used in calculating the transfer functions are between 25-60 for shear wave velocities between 200-600 m/s – having been approximately interpolated (rounded off) to vary linearly within these bounds. The computed site transfer functions indicate clear fundamental frequencies (periods) around 5.7 HZ (0.18 s) and 2.8 Hz (0.36 s) for the Missouri and Illinois sites respectively.

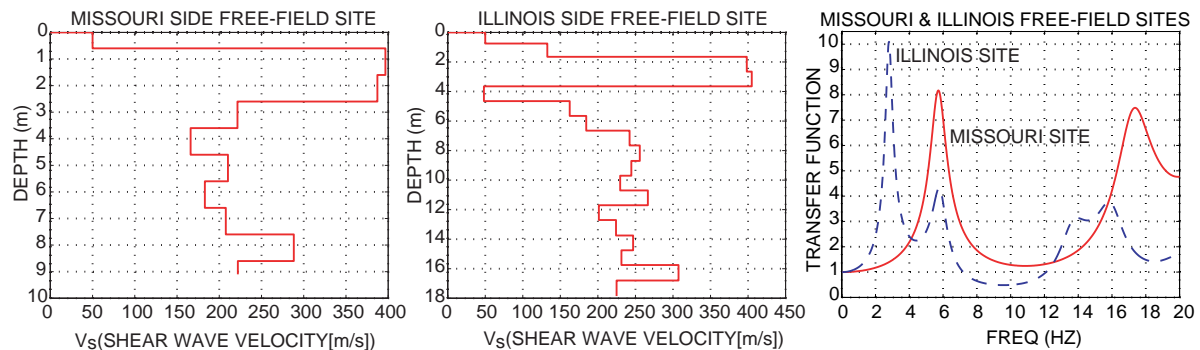


Figure 13. Shear-wave velocity vs. depth profiles and computed site transfer functions for both Missouri and Illinois free-field array sites.

Another approach in computing site transfer functions is by using recorded data. Amplitude spectra of EW motions at both MO and IL surface and downhole locations are shown in Figure 14. Also shown in the figure are the spectral ratios for each side (MO or IL) 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 around 5.5-6 Hz (0.16-0.18 s) for the Missouri site and around 2.0 Hz (0.5 s) for the Illinois site. Higher frequencies (periods) between 5.5-6.5 Hz (0.15-0.18) are also dominant on the Illinois site. In particular for the Missouri site, spectral ratios indicate likely numerically induced peaks at 1.8 and 2.6 Hz for the ratio $F1/F3$ – likely numerically induced as they vanish for spectral ratios $F2/F3$; thus, confirming the peak belonging to the fundamental mode at around 5.5-6.0 Hz (0.16-0.18 s).

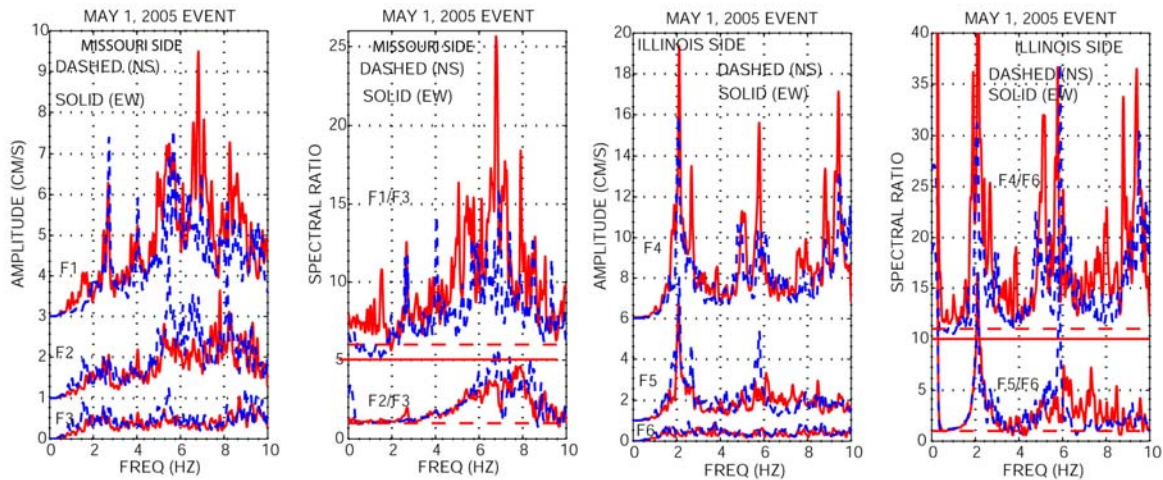


Figure 14. Amplitude spectra and spectral ratios of the free-field surface and downhole (EW) motions at the MO and IL side clearly show site amplifications at around 5.5- 6.0 Hz at MO side and at 2 and 5.5-6.5 Hz at IL side. The lower peaks for MO site are likely numerical as they disappear for the spectral ratio $F2/F3$.

CONCLUSIONS

In this paper, a new, integrated network of broad-band seismic instruments deployed on and in the vicinity of the new cable-stayed bridge in Cape Girardeau, MO is discussed. 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. Continuously-recorded low-amplitude motions can facilitate assessment of dynamic characteristics of the structure and provide a basis for estimating levels of shaking during much less frequent stronger events (as in the New Madrid Seismic Zone). Preliminary analyses of low-amplitude data including an earthquake demonstrates that (a) identification of response characteristics are successful and (b) amplified ambient vibrations caused by tower-cable-deck interactions are observed – with small amplitudes compared to those that expected from stronger shaking. In the long-term, data from these small-amplitude vibrations provide opportunities to study for rupture scenarios, material fatigue and low-cycle fatigue.

High resolution signals from low amplitude data are so good that feedback from even ambient vibrations originating at the structure and traveling to the surface and downholes are observed in detail – indicating that the structure moves the ground during stronger ambient vibrations caused by towers-cable-deck interactions.

Site response effects quantified through transfer functions using site characterization profiles or spectral ratio computations using earthquake data show very reasonable agreements in identified fundamental site periods on either side of the bridge.

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. 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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