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16. ABSTRACT

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Hardware Maintenance and, Long-term Data Collection/Analysis

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SUMMARY

In this project a description of the maintenance of the sensor monitoring systems installed on three California highway bridges is presented. The monitoring systems consist of accelerometers, strain gauges, pressure sensors, and displacement sensors which were installed on three highway bridges over the last decade: the Jamboree Rd. Overcrossing, the West St. On-Ramp, and the Fairview Rd. Overcrossing. Based on the measured sensor data under traffic and seismic excitations, the research team established baseline models of the bridges, and developed methodologies for structural health monitoring and damage assessment. The measured sensor data have provided better understanding of behaviors of highway bridges under traffic and seismic structural performance database. In total, 15 journal papers resulting from this Caltrans-sponsored project were published and 1 more is being evaluated for possible publication.

In order to improve the efficiency and reliability of data acquisition, the research team has repaired and maintained the existing data acquisition systems. Specifically, the following major tasks has been carried out: (1) maintenance of the sensors, data loggers, and power suppliers; (2) establishment of a reliable Internet-based remote access to the data loggers; (3) development of software for remote control of the data loggers through Internet; (4) data collection of the three instrumented bridges under controlled and uncontrolled traffic excitations, as well as seismic excitations; and (5) data analysis and baseline updating by taking into consideration of influence of weather and traffic.

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1. Maintenance of Monitoring Systems

Under the previous Caltrans support, maintenance of monitoring systems including accelerometers, strain gauges, pressure sensors, displacement sensors, and data acquisition devices was conducted on three highway bridges in Orange County, CA: the Jamboree Rd. Overcrossing on Rt. 261 of the Eastern Transportation Corridor, the West St. On-Ramp on the I-5 Corridor, and the Fairview Overcrossing on the I-405 Corridor. The photos of the three bridges are shown in Figure 1 and the sensor locations are shown in Figure 2.

Figure 1. Three Instrumented Bridges.

For the ultimate success of the Caltrans investment in the bridge instrumentation, it is critical to maintain the monitoring systems and analyze the long-term performance of these three bridges. Based on the collected sensor data under traffic and seismic excitations, baseline models of the bridges were established and structural health monitoring methodologies were developed. The monitoring results have been described in fifteen journal papers, as listed at the end of this document. The measured sensor data is analyzed to better understanding the behavior of highway bridge structures under traffic and seismic structural performance.

This section provides technical details of the previous and new monitoring system for each of the three bridges.

1.1 Jamboree Rd. Overcrossing

The Jamboree Rd. Overcrossing (JRO) is a typical three-span continuous cast-in-place pre-stressed post-tension box-girder bridge. The total length of the bridge is 110.9 m (366 ft) and the longest span is 152 ft. The bridge is supported on two monolithic single columns and sliding bearings on both abutments.

In total, 15 accelerometers and one displacement sensor were installed on the bridge in 2000-2002, at strategically determined locations as shown in Figure 2. Channel 16 was later found to be out of order. Therefore, the JRO monitoring system currently has 14 accelerometers and one displacement sensor (Channel 12).

A 16-channel data logger was installed at the JRO. It can be triggered either manually or automatically by earthquake ground motion. The tri-axial accelerometer at the bottom of column 3 was set up for triggering, and the triggering acceleration for each direction is 0.002g. The power supply to the monitoring system consists of a solar panel, rechargeable batteries, night time street light AC power source, and an uninterrupted power supply device (to prevent power failure due to unexpected events). During the development of this project the batteries of the monitoring system were replaced to continue monitoring the structural response.

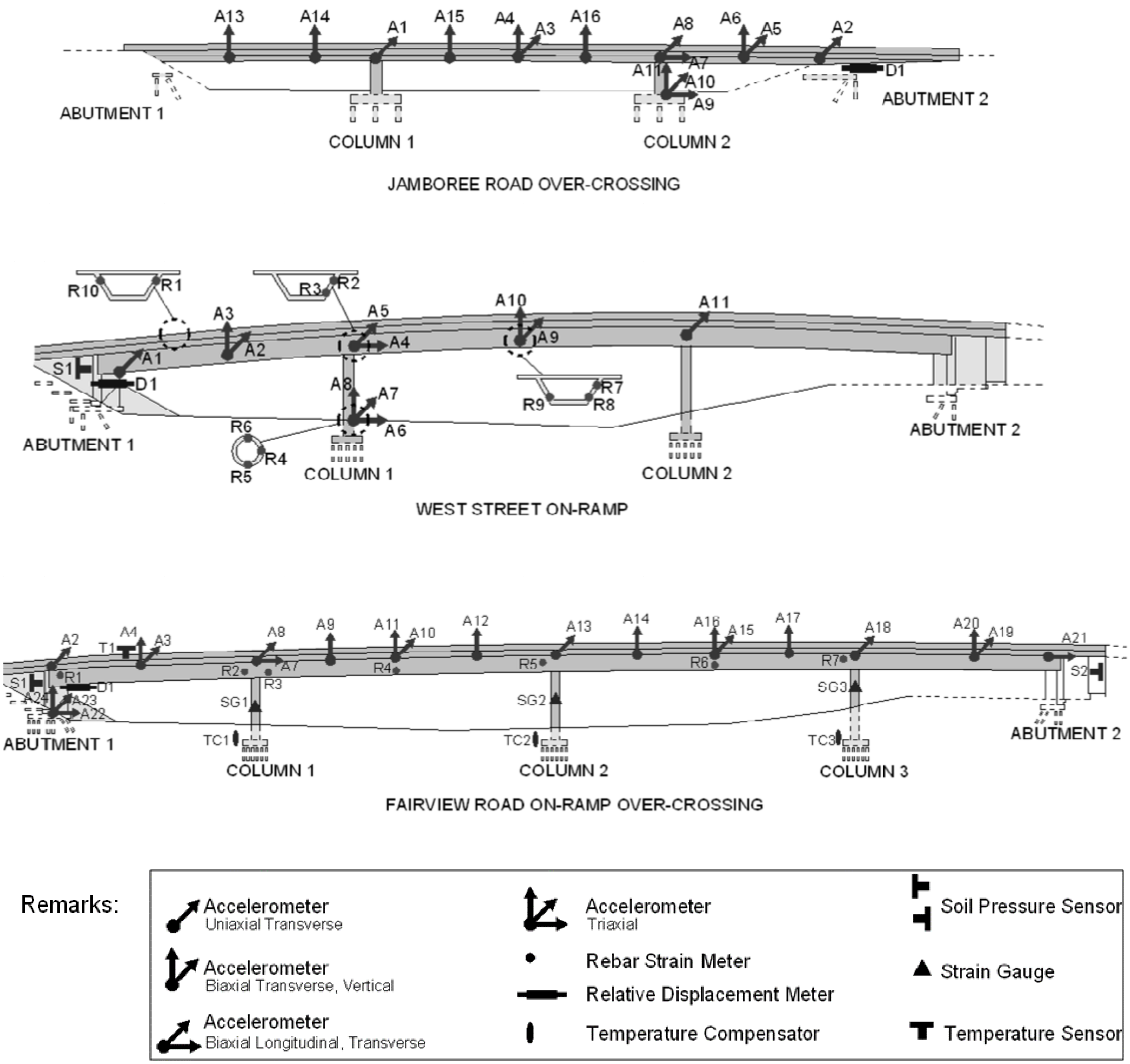

Figure 2. Sensors on Three Instrumented Bridges.

Two point-to-point antennas were installed, one at the bridge site and the other on UC Irvine campus, for real-time sensor data transmission. Software with a remote data acquisition capability was developed by the proposal team at UC Irvine based on the platform of TS-Terminal. The newly developed software was installed by the research team on a computer on UCI campus, and functions as a server that remotely controls the data logger at the bridge site, receives streaming data from the data logger, saves them in the computer and buffers them for Internet publication. However, due to the difficulty in securing the line of sight between the two antennas (located more than 6 miles apart), the wireless communication is often interrupted by the interferences on the path. Therefore further development of the wireless connection is needed.

In summary, the power supply and the data transmission do not work properly at the JRO and need to be replaced or upgraded.

1.2 West St. On-Ramp

The West St. On-Ramp (WSO) is a highly curved bridge and its instrumentation provides a unique opportunity to study curved bridges, whose performance has not been well understood. The total length of this three-span continuous cast-in-place pre-stressed post-tension box-girder bridge is 496.5 ft, in which the maximum span length is 197 ft. The bridge is supported by two fixed columns and sliding bearings on both abutments.

As shown in Figure 2, six accelerometers were installed on the WSO; one is located at the bottom of one of the columns and five are fixed to the superstructure along the center line of the girder to minimize torsion effects of the box-girder. One accelerometer is tri-axial, three are biaxial and two uni-axial, so the total number of accelerometer channels is 11. In addition to the accelerometers, 10 strain sensors were embedded in concrete at both super and sub structures during the bridge construction in 2000. Finally, one soil pressure sensor was installed at the abutment, together with one displacement sensor.

The major difficulty associated with the WSO monitoring system comes from the fact that the data logger was installed inside the box girder due to the unavailability of an easy-to-access outside space as shown in Figure 3. To access the data logger and retrieve the data recorded in the memory card, one needs to climb into the enclosed box-girder through a man hole, by placing and using a long ladder near the high-traffic I-5, which causes a safety concern. In addition, accessing the enclosed box girder requires supervision and presence of trained Caltrans personnel.

To cope with this difficulty, efforts were made to install a wireless Ethernet router and a serial to Ethernet converter inside the box-girder of the WSO. Therefore, the recorded vibration data can be retrieved from the outside of the box girder. The data is transmitted to the commercially available wireless Ethernet router, which is placed close to the man-hole in the box girder, by wired connection. The wireless router establishes a Local Area Network (LAN) by using private IP address and broadcasts the vibration data to the outside box girder. A notebook computer can receive the broadcasted vibration data from the wireless LAN router without entering the enclosed box-girder. Although limitation of transmission distance of the wireless LAN router is 165ft according to its specification, it is possible to extend this distance by installing a wireless access point to provide more convenience. Unfortunately, the wireless transmission setup is unstable and it requires more work to improve the system.

Figure 3. Access to the monitoring system inside the box girder at WSO Bridge.

In summary, the WSO monitoring system needs a reliable wireless communications solution for convenient and frequent data acquisition without accessing the data logger located inside the box girder.

1.3 Fairview Road On-Ramp Overcrossing

The Fairview Road On-Ramp Over-crossing (FROO) is a four-span continuous cast-in-place pre-stressed post-tension box-girder bridge. The total length of the bridge is 224.0 m (734.9 ft.), in which the longest span is 59.5m (195.2 ft). The bridge is supported on three monolithic single columns and sliding bearings on both abutments.

As shown in Figure 2, a total of 21 channels of accelerometers were installed on the bridge super and substructures. In addition to the accelerometers seven LVDT type strain meters were embedded in the bridge superstructure and three were embedded in one of the columns. Also, conventional resister type strain gauges were also embedded in the substructure. They are used to measure strain distribution in the reinforced concrete footing of the columns and to compare with those measured by the LVDT strain meters in the column. Two soil pressure sensors and one displacement sensor were also installed. Finally, three thermocouples were placed in the superstructure in span 1. One of them measures the outside temperature and the other two the inside temperature of the box girder.

The previous data logger was unstable and unreliable. Therefore, a new 43-channel data logger was installed at the FROO. The sensor data are acquired by retrieving an SD memory card inside the data logger manually.

2. Internet-based remote access to the data loggers

In order to improve the efficiency of long-term and frequent data acquisition, a more easy way to access data logger is needed and Internet accessible equipment setup can resolve this problem. The research team installed Internet-based remote accessible data logger at all of the three monitoring systems on the bridges. In particular, the access inside the box girder at the WSO is no longer required to retrieve the data which reduces the risk of accidents during the bridge monitoring.

The research team contracted a commercial wireless Internet service for the remote data acquisition. This Internet-based remote access will enable the researchers at UC Irvine and engineers at Caltrans to stay connected to the monitoring system on the bridges, to schedule automated data acquisition, and to acquire sensor data in real time whenever needed. Figure 4 shows a basic scheme of the installed Internet-based remote access to the data-logger.

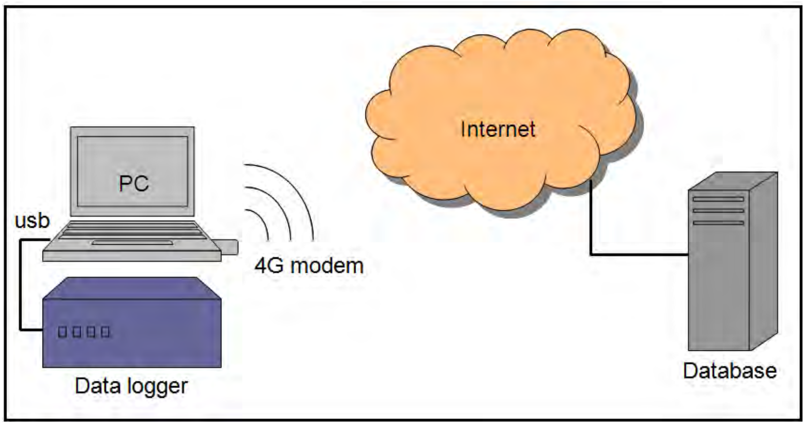

Figure 4. Internet-based remote access to data-logger(recorder).

3. Hardware Maintenance

At the Jamboree Bridge the power supply was checked and it was necessary to clean the solar panel and replace the batteries located under the superstructure. After maintenance of the power supply the research team replaced the data-logger. In order to change the data-logger the cables were replaced and the channels were re-ordered to make easier for post-processing data. Afterwards, the Internet-based remote access to the data logger was implemented.

At Fairview Bridge site, the research team checked all the cables before changing the data-logger. It was found the cables needed to be replaced. The new cables were installed using a reference table located at the bridge site. Then, the data-logger was replaced and the digital filter was implemented in order to get a better quality of the data. Afterwards, the Internet-based remote access to the data logger was installed.

Finally, the monitoring system at the West Street On Ramp Bridge was inspected. Although the data-logger was working properly a new data-logger was needed to improve the quality of the data. Also, an Internet-based remote access to the data logger was implemented in order to allow the data acquisition from the outside of the bridge.

4. Improvement of Data quality

Figure 5 shows a comparison between a sample data recorded at the WSO before and after the installation of the new data-logger. Although the two data look the same, the new data-logger allows for more options. In Figure 5 the time step of the old and new data-logger are 0.01s and 0.005s respectively. It is expected the new data-logger will work properly during at least eight years depending on the sensor performance. Unfortunately, some of the sensors are located inside the box girders where it is practically impossible to access. Therefore, if some of those sensors (as it occurred at the FROO Bridge) stop working the monitoring of the bridge will continue using the remaining sensors only.

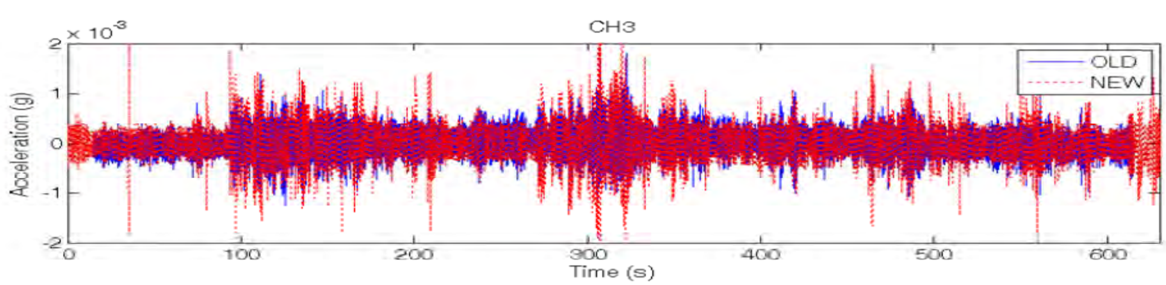

Figure 5. Comparison between vibration records at channel 3 before (OLD) and after (NEW) the replacement of the data-logger at WSO.

5. Software for remote control of the data recorders through Internet

In order to improve the remote control and data acquisition through Internet, software previous developed at UCI was upgraded with new functions. This software enhances the data transmission stability and reliability. The updated software was installed on a computer on UC Irvine campus, and can function as a server that receives streaming data from the data logger on the remote bridge site, saves them in the local computer and buffers them for Internet publication. The new software has algorithms to accommodate data transmission errors during wireless communication, thus suffering fewer interruptions during data transmission.

Figure 6 shows remote real-time acceleration data recorded at JRO.

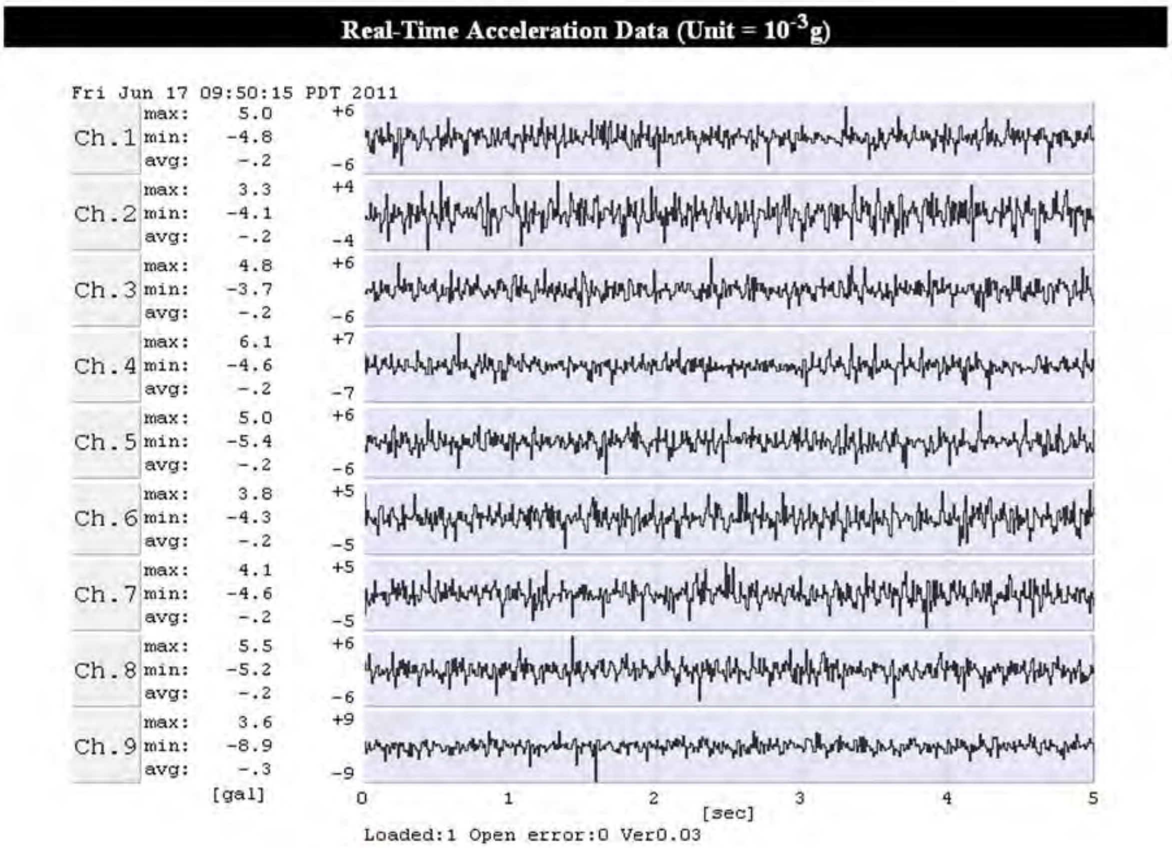

Figure 6. Remote Real-Time acceleration data recorded at JRO.

6. Data collection under controlled and uncontrolled traffic excitations and under seismic excitations

An extensive data collection was conducted since 2002. The available data were recorded under different loading conditions including controlled and uncontrolled traffic excitations. This enables the investigation of the vehicle-bridge interaction and furthermore the influence of traffic on the bridge dynamic behaviors. Typical response acceleration time-histories recorded at 11 channels at the WSO Bridge under uncontrolled traffic are shown in Figure 7.

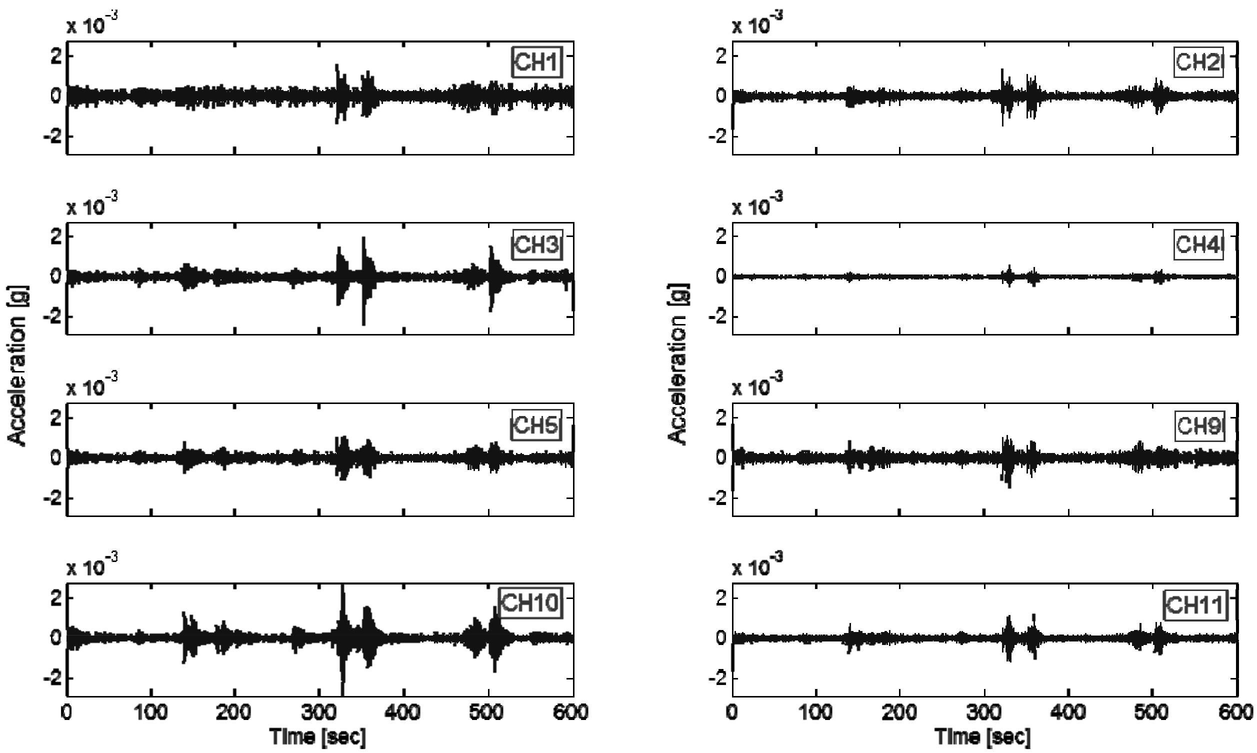

Figure 7. Response acceleration time-histories recorded at WSO Bridge.

Figure 8 shows response acceleration time-histories under controlled traffic excitations at the WSO Bridge, in which a heavy truck, shown in Figure 8, was driven on the bridge at different speeds and alongside different lanes.

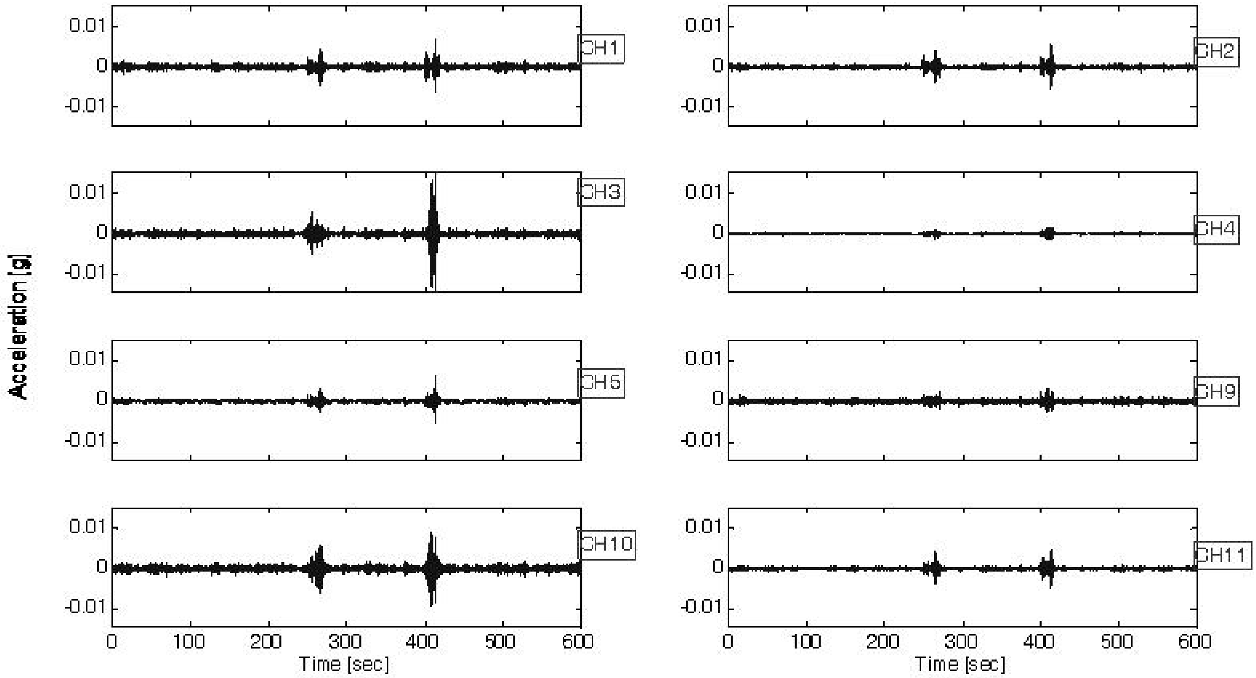

Figure 8. Response acceleration time-histories recorded at WSO Bridge during controlled tests using a Caltrans water-truck.

Figure 9. Water truck driven over the WSO bridge during the traffic controlled tests.

Also, data were collected during earthquakes. Table 1 lists six earthquakes that have been recorded at the bridge site. Figure 10 shows the response of both JRO and WSO Bridges to Yucaipa earthquake at three different sensor locations. To continue with the structural analysis of bridges under seismic demands, the data collected in this task is highly precious since the project team's previous data analysis has shown that the dynamic properties of the structure vary with the intensity of the earthquake.

Table 1 Seismic records obtained at WSO Bridge

Event Name	Magnitud	Date	Time	PGA			Distance to epicenter	Depth
				Longitudinal	Transverse	Up		
	M_w	*mm/dd/yy*	*Pacific Daylight Time*		*g*		*km (mi)*	*km (mi)*
Anza	5.2	06/12/05	08:41:46 AM	0.005	0.011	0.002	129 (80)	14.1 (8.8)
Yucaipa	4.9	06/16/05	01:53:26 PM	0.006	0.018	0.005	88 (55)	11.8 (7.3)
Chino Hills	5.5	07/29/08	11:42:15 AM	0.086	0.367	0.045	21 (13)	14.7 (9.1)
Inglewood	4.7	05/17/09	08:39:36 PM	0.013	0.026	0.007	41 (25)	15.1 (9.4)
Pico Rivera	4.4	03/16/10	04:04:00 AM	0.010	0.019	0.004	24 (15)	18.9 (11.7)
Calexico	7.2	04/04/10	03:40:42 PM	0.006	0.007	0.004	300 (186)	10.0 (6.2)

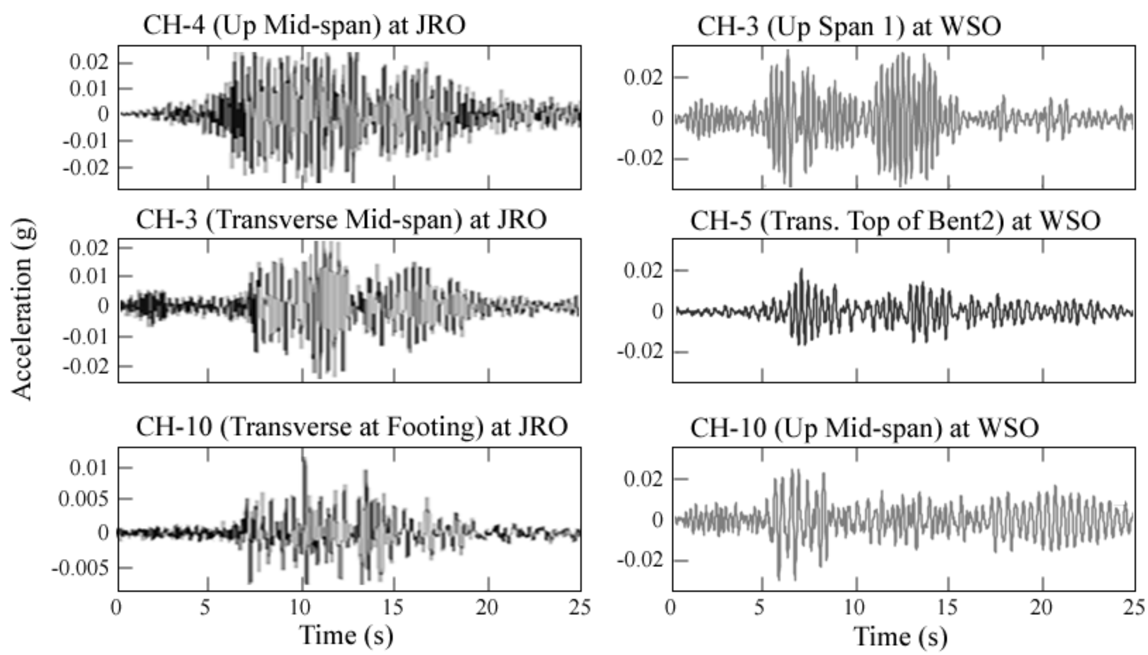

Figure 10. Response acceleration recorded at JRO and WSO Bridge during Yucaipa Earthquake.

Figure 11 shows the variation of WSO natural frequencies as the ground motion intensity measure (PGA) increases. It is evident the stronger the earthquake the smaller the natural frequency of the bridge. However, Chino-Hills and Calexico events are not included in Figure 11 The former is not included because its PGA is very high relative to the others and the latter because its remoteness to the bridge site may have an effect on the SI results. In future studies these findings will provide valuable information for the further improvement of the Caltrans seismic design models and criteria.

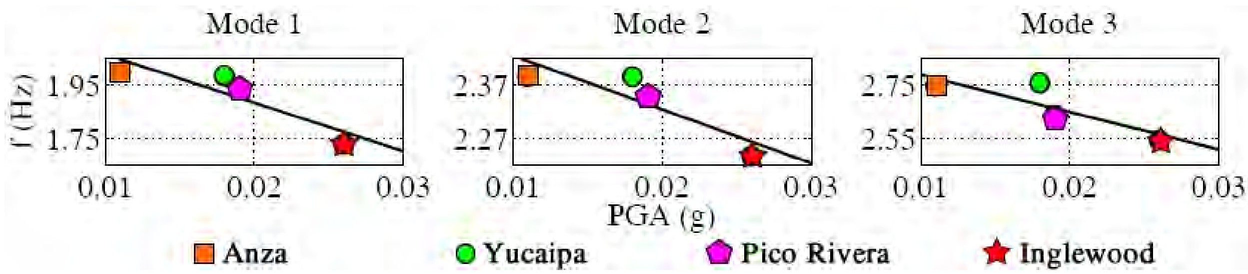

Figure 11. Frequency dependence on earthquake peak ground acceleration (PGA) at WSO.

Finally, data were collected from the strain sensors at the WSO and the FROO. The strain measurement can provide direct information regarding the structural health condition. Figure 12 shows strain measurements at the WSO under controller traffic. The strain meters were placed at locations R1 – R10. In Figure 12 a Caltrans water truck was parked at different locations (L-1 to L-5) while it was slowly moving along the inner lane 2ft from the edge of bridge (T-1). The maximum strain is related to tension forces at sensor locations R-9 and R-8 caused by the truck located at position L-4 (mid-span). On the other hand the minimum strain relates to compression forces at sensor location R-6 when the truck is located at position L-3.

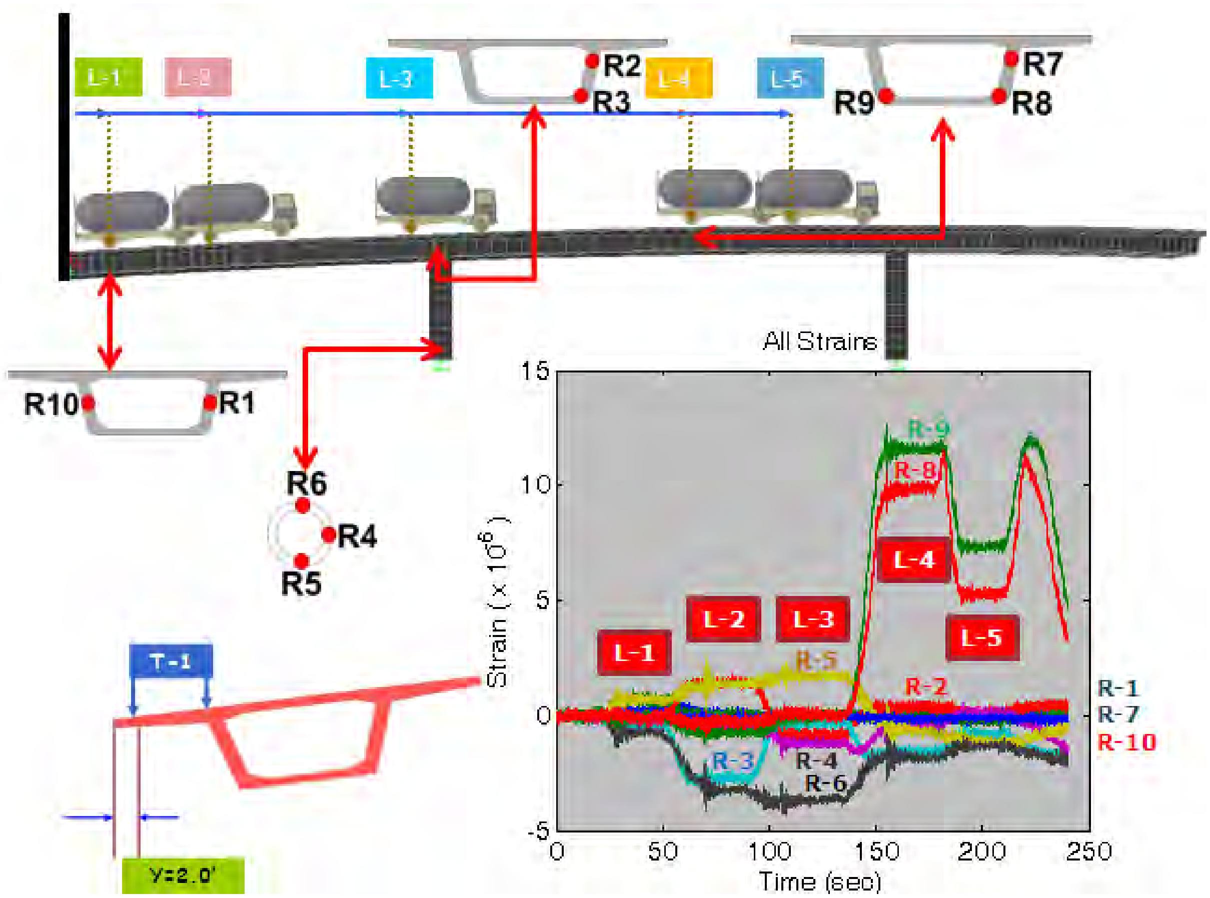

Figure 12. Strain measurements at WSO during controlled traffic vibration test. Remarks: L denotes the position of the truck, R denotes strain meter, T denotes transverse position of truck.

7. Data analysis, database development, and baseline updating

The sensor data collected in Task 4 was stored into a database for each of the three bridges. These databases contain the bridge response to two different types of loading conditions (traffic excitations, and earthquake excitations) and different weather (temperature and humidity) conditions.

Figure 13 shows the variations of the first four modal frequencies over the 5-year monitoring period at JRO. The variation in the identified modal frequencies is in the order of ±10% of that obtained in the very beginning of the monitoring (Soyoz and Feng 2009).

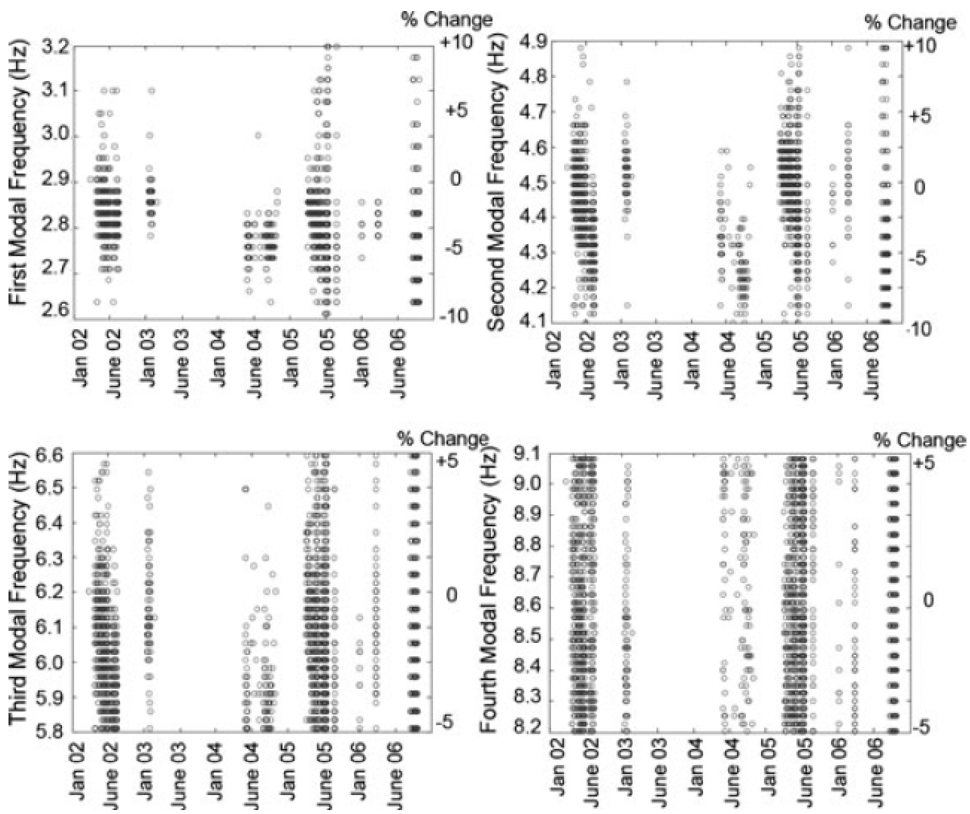

Figure 13. Variation of JRO natural identified natural frequencies (Soyoz and Feng 2009).

In Figure 14 a decreasing of the first and second identified frequencies at JRO is shown. The decrease is of approximately 5% in five years.

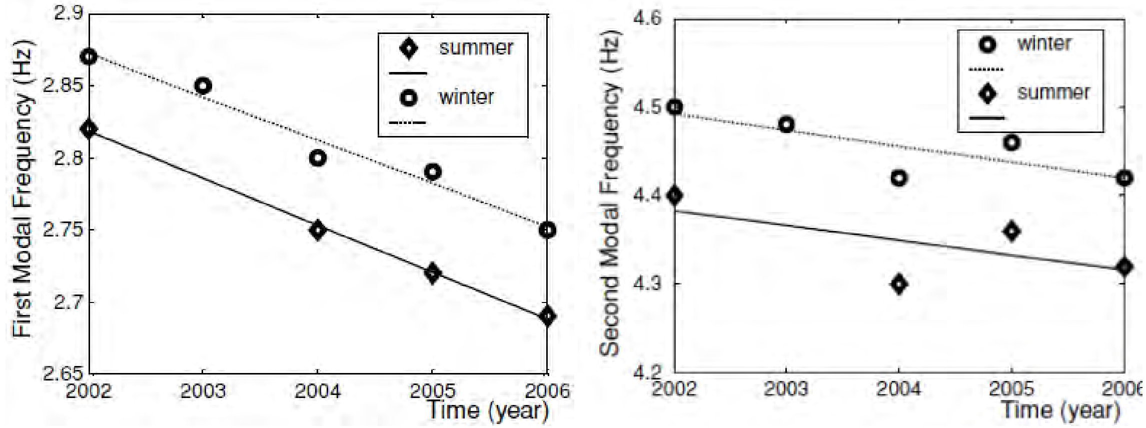

Figure 14. Decreasing of the first and second natural frequencies at JRO (Soyoz and Feng 2009).

Figure 15 shows the variation of the WSO first four identified natural frequencies. Similar to JRO there is a linear and gradual decreasing of the frequencies. Whether this decrease relates to structural degradation or not it shows the bridge system is changing its behavior through time. The linear regression shows the reduction on frequencies is approximately 7-8% for the first and third frequencies and 5% for the second mode.

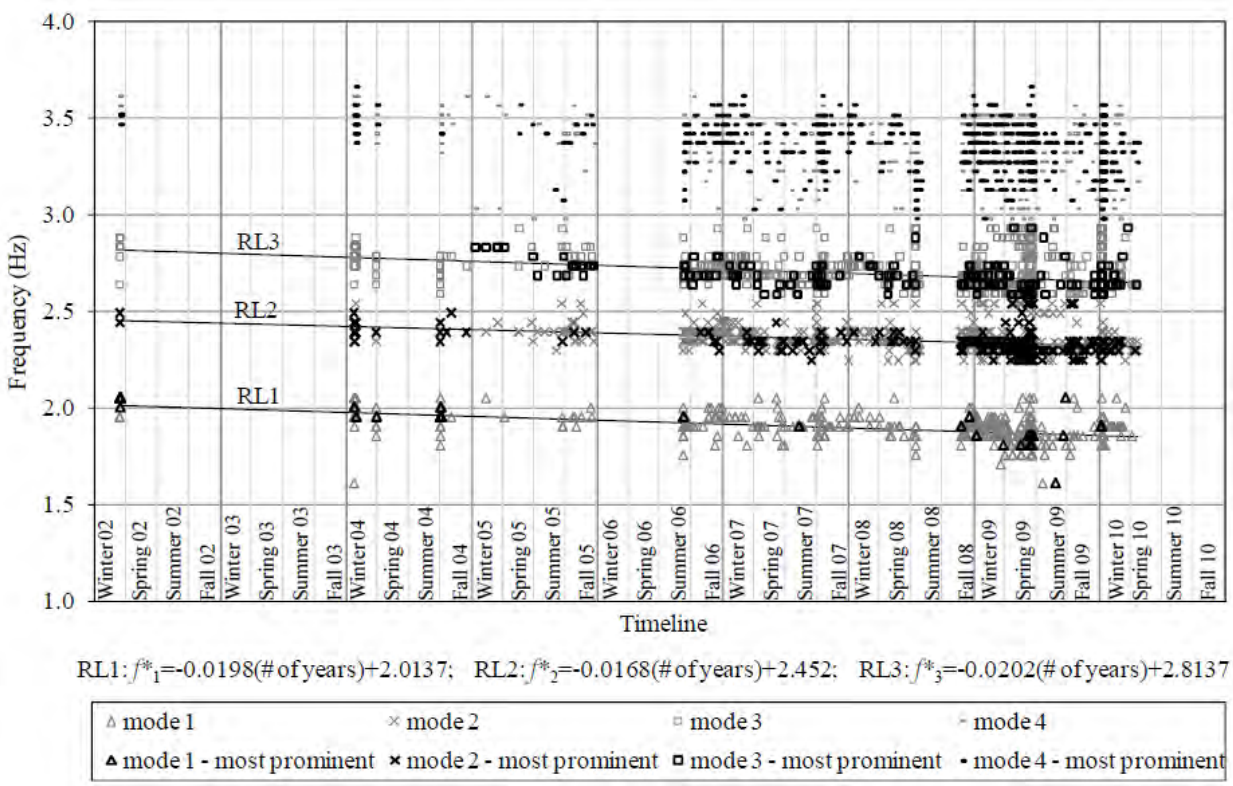

Figure 15. Long-term monitoring of WSO Bridge natural frequencies.

In Figure 15 the solid markers indicates the most dominant mode in the frequency domain. It is clear the second mode (vertical bending of deck) is dominant in most cases. This is due to the increasing amount of traffic on the bridge which mobilizes the deck in the vertical direction. Although not shown in this report similar results are observed for the FRO Bridge.

Finite element (FE) models for the three bridges were developed. The models were calibrated using the dynamic properties, i.e. frequencies and mode shapes, obtained from the measurements. The calibrated models for the JRO and WSO were updated over the time based on sensor measurements. The long-term change in the bridge baseline models was studied. Structural parameters, i.e. superstructure and substructure stiffness were identified from the FE models. Figure 16 shows the stiffness degradation of the JRO superstructure estimated using Artificial Neural Networks (ANN). A 2% decrease of the superstructure stiffness is observed over five years of monitoring.

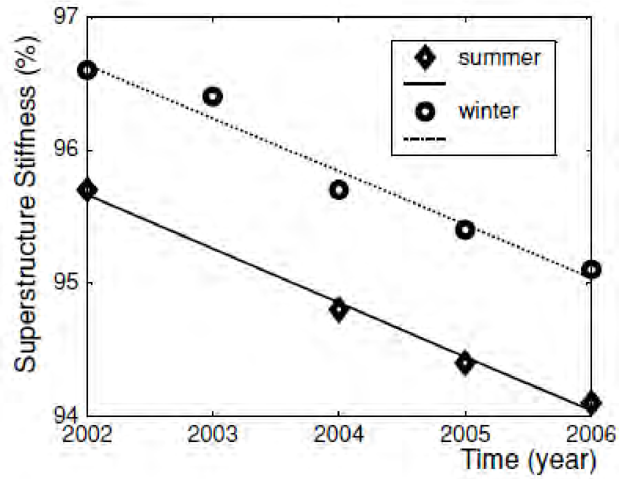

Figure 16. Superstructure stiffness degradation at JRO Bridge.

Figure 17 shows the stiffness degradation of both superstructure and columns of the WSO Bridge estimated using the Finite Element Model Optimization technique Direct Search (DS).

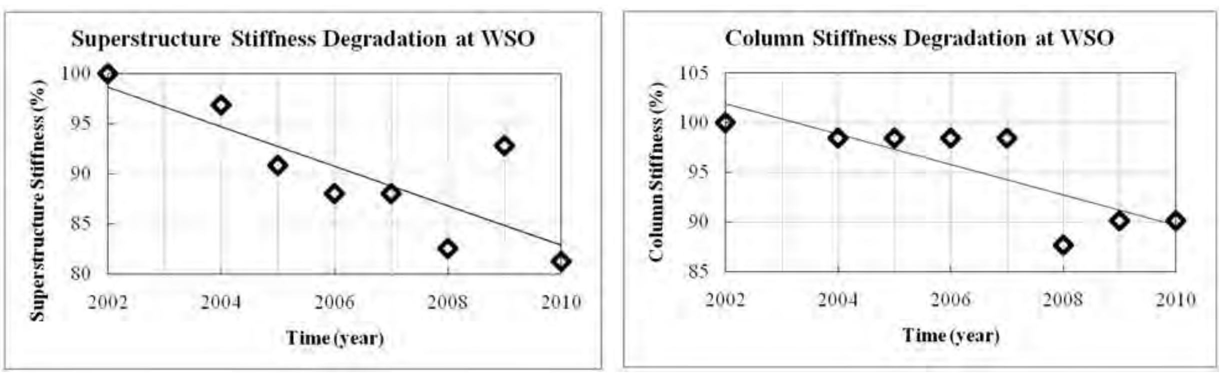

Figure 17. Superstructure and column stiffness degradation at WSO Bridge.

The superstructure stiffness shows a variation of approximately 20% in eight years of monitoring whereas the column stiffness shows a variation of approximately 10%. This information is valuable for further improvement of the bridge design/analytical models and criteria. The FE model updating will also play an important role in the continued development of the methodologies for bridge structural health monitoring and damage assessment.

Table 2 shows a comparison of the long-term monitoring of the three bridges' natural frequencies. A gradual decreasing along the time-line can be observed for all the three bridges. However, relevant information is missing as in some of the years of monitoring there is no available data due to malfunctioning of the monitoring system during that time. It can also be observed that the natural frequency relates to the longitude and number of spans of each bridge.

In this case the longest bridge (FROO) has the smallest natural frequency whereas the shorter bridge (JRO) has a larger natural frequency.

Table 2 Yearly Average Bridge Natural Frequencies

Bridge	f_1									
	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
JRO	2.85	2.85	2.77	2.74	2.69	--	--	--	--	--
WSO	2.04	--	1.97	1.95	1.91	1.91	1.91	1.88	1.85	1.85
FROO	--	--	--	--	1.51	--	--	--	1.49	1.49
Bridge	f_2									
	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
JRO	4.45	4.49	4.38	4.43	4.39	--	--	--	--	--
WSO	2.44	--	2.41	2.38	2.36	2.35	2.35	2.32	2.31	2.34
FROO	--	--	--	--	2.01				1.91	1.97
Bridge	f_3									
	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
JRO	6.01	6.11	5.91	6.02	5.91	--	--	--	--	--
WSO	2.84	--	2.78	2.77	2.71	2.68	2.71	2.66	2.64	--
FROO	--	--	--	--	2.31	--	--	--	2.25	2.27

8. Conclusions

Maintenance of the monitoring system at three bridges (JRO, WSO, and FROO) is reported. New data-loggers enhance the quality of the recorded data which in turn allows for more accurate results of the post-processing.

An Internet-Based remote data acquisition was installed at the three bridges as the new data-loggers allow the connection of a wireless device. This remote access allows for researchers and engineers to monitor the bridge dynamic properties and structural response without the need of going to the bridge site.

From the datasets available at the three bridges a linear and gradual decrease of the lower identified natural frequencies is detected. This decrease is attributed to the aging of the structural system rather than any significant damage.

FE models of the three bridges were developed and calibrated with the available measurements. The models are utilized to identify changes of the structural stiffness. For the JRO the superstructure stiffness decreases approximately 2% in five years of monitoring. In the case of WSO a decrease of the superstructure stiffness of approximately 20% in eight years of monitoring is detected whereas the column stiffness suffered 10% decrease in eight years.

In future studies the FE models will be analyzed in more detail so the effect of stiffness reduction is studied. In addition other techniques will be applied to the data to clarify whether the change in frequencies can be utilized as an indicator of structure deterioration. In this manner engineers could potentially apply preventive maintenance before structural damage occurs. Finally, the data obtained from the strain gauge will be correlated with the health condition identified using the vibration measurement made by the accelerometers.

Appendix A

A.1 Replacement of Data-loggers

For the three bridges the data loggers were replaced (see Figure 18). In addition the deteriorated rechargeable batteries in the JRO were replaced and the solar panel was cleaned to maintain its optimum performance. The out of order sensors were diagnosed and they will be repaired.

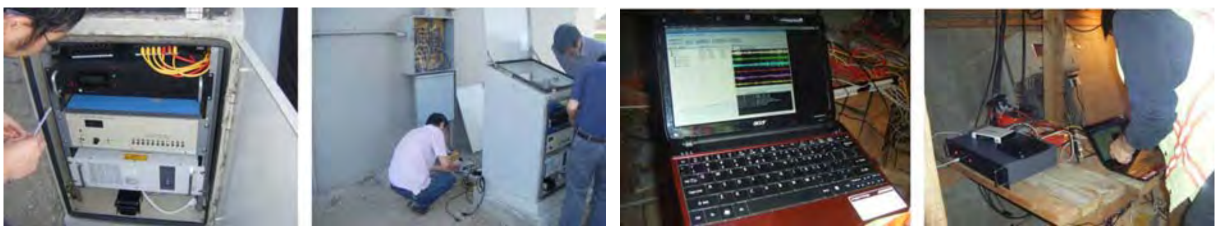

Figure 18. Replacement of the data-logger at FROO and WSO

The new data-logger specifications are listed in Table A-1. Some features improve the quality of the acquired data thus enhancing the accuracy of the analyses. It should be noticed the new data-logger stores the data either in an SD or a USB memory instead of a PCMCIA card as in the previous data-logger. Using either SD or USB memory cards facilitates the storage of data. Figure 19 shows a simple scheme of the new data-logger.

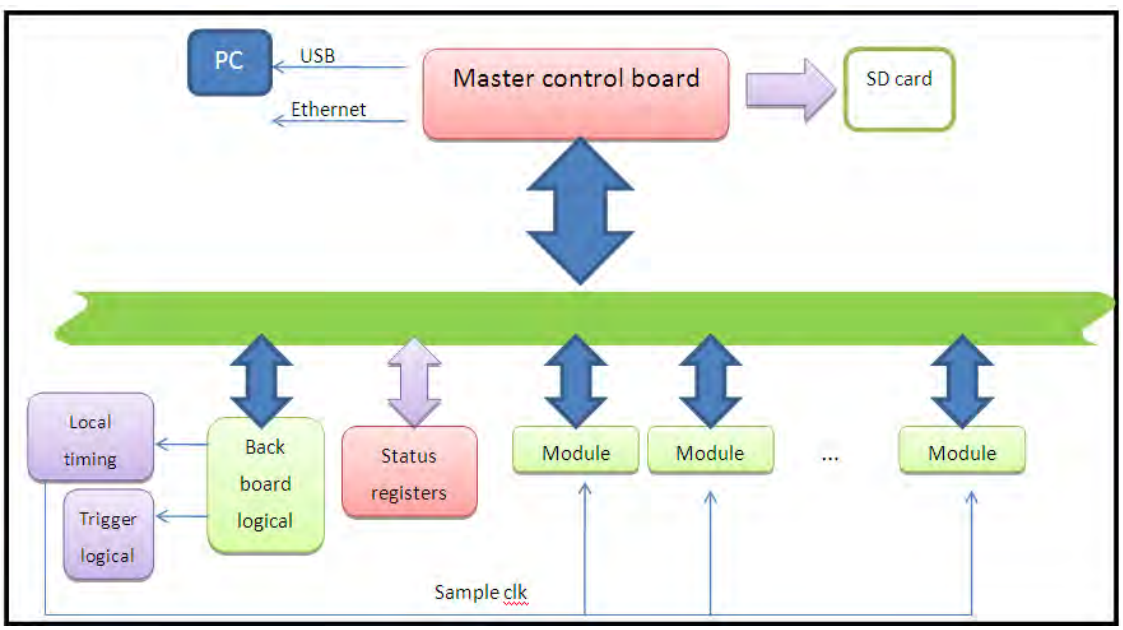

Figure 19. Scheme of the new data-logger

Using the new data-logger the bridge response can be continuously recorded for more than an hour. On the contrary, the previous data-logger could record for a maximum of only ten minutes which caused a total of five gaps in one hour of monitoring.

Table A-1. New data-logger specifications.

Input	
Max. channel	48
Input range	±10V/±5V
Input signal type	Differential
Input impendence	>100GΩ
Acquisition	
Sampling rate	50Hz/100Hz/200Hz
Chan.-Chan. Skew	None Simultaneous sampling at all channels
Acquisition modes	Continuous/Trigger
Anti-alias filter	60-order FIR digital filters on each channel
ADC bit width	16 bits
Dynamic range	>90dB (to be confirmed)
Trigger	
Trigger modes	Higher: higher than upper threshold Lower: lower than lower threshold In-window: between two threshold Out-window: outside two threshold
Trigger voting	Sum of weighted trigger source
Advanced trigger modes	STA/LTA
Storage	
Type	SD card
File system	FAT 16
Recording time	Dependent on SD card capacity. ~15 hr (1GB, 200Hz, 48ch)
Power Supply	
Type	ATX 2.0
Input	AC110V, ±20%
Power consumption	50W
Housing	
Size	485mm x 260mm x 88mm
Weight	~5.5kg
Mounting	2U rack chassis
Others	
Synchronization source	GPS/RTC/Ext.
Communication types	RS232/USB/Ethernet
Operating temp.	-45~85°C

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