SHM APPLICATION FOR MONITORING EXISTING BRIDGE PIER DURING CONSTRUCTION IN CLOSE PROXIMITY

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The Madawaska River Bridge No. 1 is located on provincial Route 114 in Edmundston, New Brunswick, in Canada. Edmundston Energy recently commenced the construction of a hydroelectric dam on Madawaska River which includes the construction of a power channel in the immediate vicinity of one of the bridge pier foundation. The channel is located approximately 1.2 m away from the face of the pier foundation horizontally, and its invert is approximately 4 m below the foundation bottom.

To ensure safety and integrity of the bridge structure during the construction a Structural Health Monitoring system (SHM) was installed and baseline data gathered for a period of one-week preceding the commencement of the construction activity in the immediate vicinity of the pier.

The monitoring system is comprised of displacement transducers, tilt meters and strain gauges located at key locations. The data is gathered and transmitted to a remote base server through the use of a wireless cellular network. A server-based program stores and displays data in real-time and generates alarm emails to selected personnel if predefined alarm parameters for strain, displacement and temperature are exceeded. The behaviour of the pier has been monitored for over eight months after the completion of work. A review of the monitoring data has shown that the various parameters monitored remained within the range stipulated by the bridge owner. Due to space limitations only the displacement data will be discussed in this paper.

This paper demonstrates the practical application of SHM for managing risk during construction. The baseline data helps identify the influence of factors such as the temperature, wind, traffic etc. which could otherwise be construed as the effects due to construction activities.

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ABSTRACT: The Madawaska River Bridge No. 1 is crosses over Madawaska River in Edmundston, New Brunswick, in Canada. Edmundston Energy recently completed the construction of a power channel running only 1.2 m away from the face of the pier foundation with its invert approximately four meter below the bottom of the pier base.

To ensure safety and integrity of the bridge structure during the construction a Structural Health Monitoring system (SHM) was installed and baseline data gathered for a period of one-week preceding the commencement of the construction activity in the immediate vicinity of the pier.

The behaviour of the pier was monitored for over eight months after the completion of work. A review of the monitoring data has shown that the various parameters monitored remained within the range stipulated by the bridge owner.

This paper demonstrates the practical application of SHM for managing risk during construction. The baseline data helps identify the influence of factors such as the temperature, wind, traffic etc. which could otherwise be construed as the effects due to construction activities. Due to space limitations only the displacement data will be discussed in this paper.

1 INTRODUCTION

The Madawaska River Bridge No 1 is located to the immediate downstream of an existing dam on Madawaska River in Edmundston, NB, Canada. This is a four-span bridge of reinforced concrete construction with two abutments, East Abutment and West Abutment and three piers designated Pier 1 through 3 starting from the East Abutment. The piers are supported on spread footings resting on bedrock. The bridge superstructure is a combination of cast-in-place and prestressed concrete girders. Each end span, comprising of six reinforced concrete girders cast integrally with the pier, cantilevers approximately 12 m beyond the pier into adjacent span. Each intermediate span is comprised of six precast prestressed concrete girders (Fig. 1).

Figure 1. View of Pier 1, Madawaska River Bridge No. 2 during power channel construction.

1.1 Motivation for Monitoring

Edmundston Energy generates hydroelectric power from an existing dam over Madawaska River in Edmundston, New Brunswick, Canada. In order to increase its generating capacity, Edmundston Energy has constructed a new power generating station to the downstream of Madawaska River Bridge No. 2. The work includes the construction of a new power channel that runs adjacent to the pier foundation with its invert approximately 2.4 m below the bottom of the foundation.

The sedimentary bedrock below the foundation had near vertical bedding and was highly fractured. The geotechnical investigation identified possible loss of bedrock under the pier foundation due to spalling during excavation in its immediate vicinity as an area of concern. Such loss could potentially cause the movement of the pier. It was recommended that the rock strata below the pier be stabilized by means of rock anchors and concrete wall and the pier be actively monitored during construction in its immediate vicinity (Levesque and McAfee).

It was decided to implement a Structural Health Monitoring (SHM) system for monitoring the pier. It was envisaged that the system would be able to send alarm emails to designated personnel automatically if any of the monitoring parameters exceeded their predefined limits. This would allow them to take corrective measures in a timely manner.

1.2 Monitoring parameters

The loss of material from beneath the foundation near the face of excavation could result in tilting of the base which would affect the stability of the pier. There was potential for rotation of the foundation, pier, and the superstructure as a one single unit. Due to the geometry of the structure, a 0.5 mm settlement of the foundation along one edge would translate into a 2.5 mm horizontal movement of the superstructure at deck level. The settlement would also possibly cause the pier to tilt and develop bending

stresses at the base of the pier. Based on the above criteria the following three parameters were identified and selected for monitoring:

- Displacement – horizontal at deck level and vertical at bearing level
- Tilt – longitudinal and transverse tilt at pier top and bottom
- Concrete Strain – vertical direction at pier bottom

1.3 Limiting Values

The limiting values for the monitoring parameter were specified by the bridge owner as shown in Table 1.

Table 1. Monitoring Parameters and their limiting values

Parameter	Horizontal displacement at deck level (mm)	Tilt (deg.)	Concrete strain (με)
Limiting value	± 2.5	±0.007	+45, -200

1.4 Sensor and system selection

The sensor selection was based on obtaining maximum information with minimum number of sensors. The main objective of monitoring was to detect any permanent movement of structure during construction in the vicinity of Pier 1 and for at least six months thereafter to ascertain that there were no residual post-construction effects on its stability. It was determined that data acquisition at one-minute interval would be able to provide adequate information on the status of the pier without accumulating excessive volume of data.

A combination of vibrating wire and MEMS sensors was selected. Each sensor also incorporated a temperature sensor for measuring temperature in its vicinity.

The selected data acquisition system comprised of multiplexers, a data logger unit and a backup power supply unit, all housed in a climate controlled enclosure. It was decided to use a cellular modem to transmit data from the site to the base station located in Halifax, Nova Scotia. Proprietary data analysis and display software was selected for automatic data processing and included automatic alarm generating capabilities.

1.5 System installation and commissioning

The installation of the sensors and the system were carried out in late February 2010. The strain gauges were numbered SG 1 through SG 4. The displacement transducers were designated DT 1 through DT4. The bi-directional tilt meters were designated R1U and R2D with suffix A and B indicating East-West and North-South directions respectively. The designation, location, and the orientation of each sensor are graphically shown in Figures 2 and 3.

Cellular communication between the data logger and the base station was established and verified and the system commissioned. Baseline data was collected for a period of one week prior to the commencement of any excavation activity in the vicinity of Pier 1.

1.6 User data access

Selected personnel were provided password protected access to the base station through internet to review data as and when needed.

1.7 Warning alarms

The excavation in close proximity of the pier foundation was a cause for concern and required constant monitoring on a continual basis. While the data would be reviewed manually at regular intervals, the likelihood of missing a significant change in the data could not be ruled out. To avoid such a situation an automatic alarm generation system was incorporated. The system was capable of sending warning emails to designated personnel if any of the sensor response exceeded its predefined threshold. A follow up email would be sent as soon as the sensor response returned within its normal range.

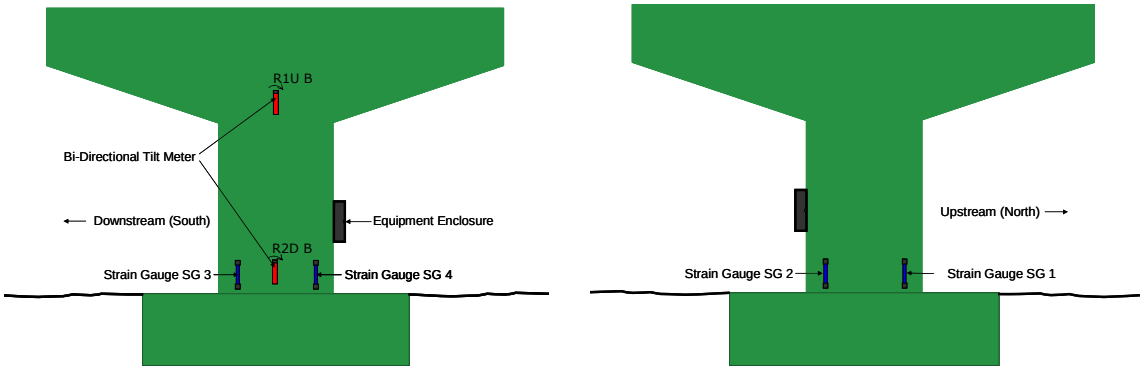


Figure 2. View of Pier 1 (L) looking East and (R) looking West showing

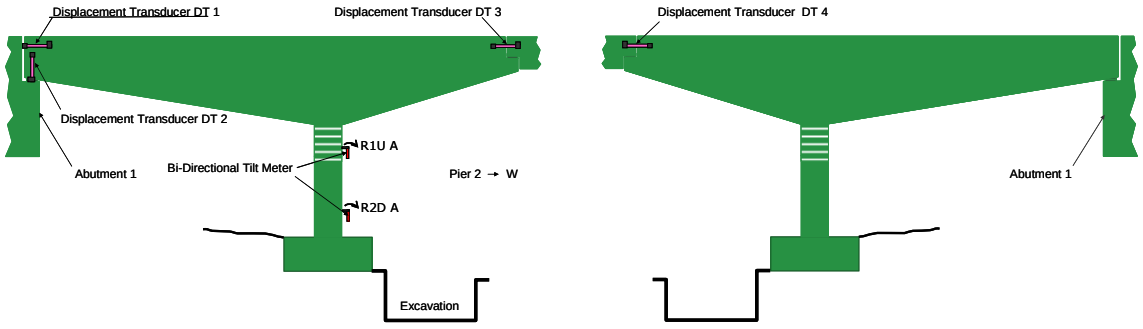


Figure 3. View of Span 1 (L) looking South and (R) looking North showing sensor locations

1.8 Reporting

A written report was submitted to stakeholders' key personnel on a weekly basis. Each report was self-contained and included information on sensor designation, sensor locations, and alarm thresholds. The report presented data for each sensor in a chart form covering the preceding seven-day period followed by comments on any unusual occurrences and a breakdown of alarms generated during the reporting period.

2 POST COMMISSIONING DATA REVIEW

2.1 General

The data is being collected and transmitted to the base station for processing and display. The discussion will include effects of temperature effects, foundation settlement, effectiveness of monitoring, and conclusion. Due to space limitations only the displacement data is being presented and discussed in this section. Displacement transducers DT 1 and DT 2, located at the abutment, measure the horizontal and the vertical movement, respectively (Figure 4 Left & Middle). Displacement transducers DT 3 and DT 4, located at the free end of the cantilever, measure the horizontal deck movement at the north and the south faces, respectively (Figure 4 Right).

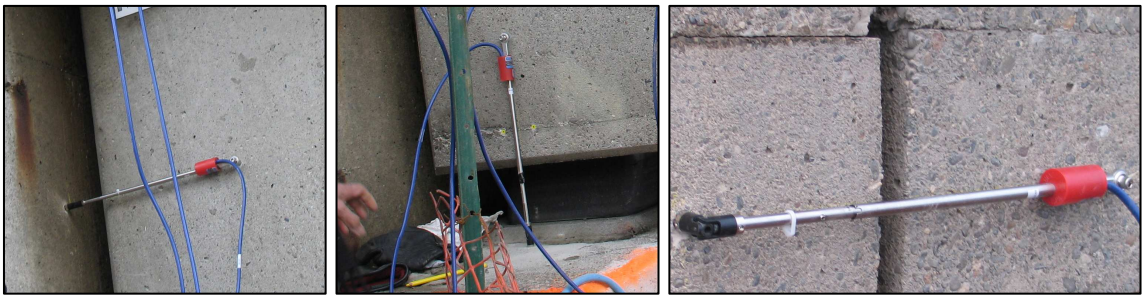


Figure 4. (left) DT 1, (middle) DT 2 and (right) DT 3

2.1.1 Distinguishing effects of temperature variation and foundation settlement

There are two disparate data patterns that would distinguish between the displacements caused by the daily and seasonal temperature variations and those caused by the settlement of the pier foundation. This is illustrated graphically in Figures 5 and 6. With an increase in the temperature the superstructure would expand and both transducers DT 1 and DT 3 would record a corresponding reduction in the measured gap, albeit of differing magnitudes due to the difference in the length of each segment of the superstructure. Similarly, a fall in the temperature would lead to a corresponding increase in the measured gap (Figure 5 L).

The settlement of the foundation would lead to the rotation of the pier and the superstructure as a single body. This would lead to an outward movement of the superstructure thereby, increasing the gap between the superstructure and the abutment measured by transducer DT 1 on one hand, and reducing the gap between the cantilevered end and the girders supported on brackets, measured by transducers DT 3 and DT 4. There would also be an increase in the vertical gap between the abutment and the superstructure measured by transducer DT 2 (Figure 5R).

The two data patterns are summarized in Table 2.

Table 2. Gap change pattern due to temperature variation and pier settlement

Effect	DT 1	DT 2	DT 3/DT 4

Temperature Increase	–	Decrease	Decrease	Decrease
Temperature Decrease	–	Increase	Increase	Increase
Settlement		Increase	Increase	Decrease

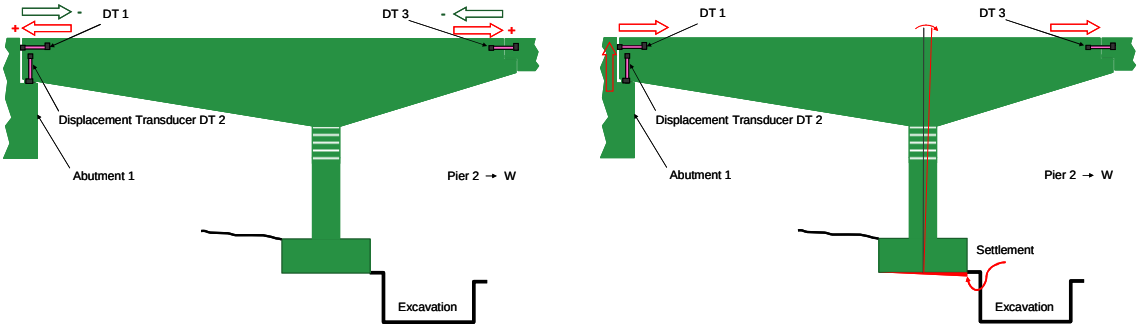
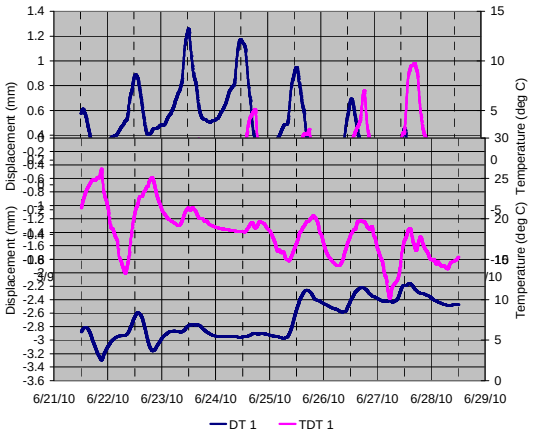
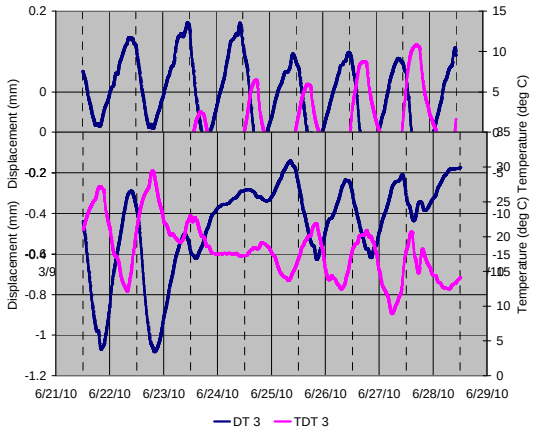


Figure 5. Superstructure movement due to (L) temperature variation, (R) foundation settlement

2.1.2 Temperature effects –seasonal variations

The data indicates that the seasonal temperature variations in Edmundston range from -25^{0}C to +35^{0}C. This can result in significant expansion or contraction of the bridge superstructure. The sensors were installed and zeroed at about 2^{0}C. Hence, during summer months when the temperatures rise above about 25^{0}C the magnitude of the expansion at the longer segment of the superstructure exceeds (DT 1) the threshold value for the warning alarm. It is possible to assess the stability of the pier by comparing the data pattern as discussed in Section 2.1.1 A quick review of the data pattern described in 2.1.1The review of the data also indicates that the orientation of this of the bridge can also result in differential expansion and contraction of the bridge superstructure. To illustrate this phenomenon the displacement and temperature data covering a one week period was plotted at three different stages and shown in Figures 6





through 11.

Figure 6. Displacement patterns in March 2010

Figure 7. Displacement patterns in June 2010

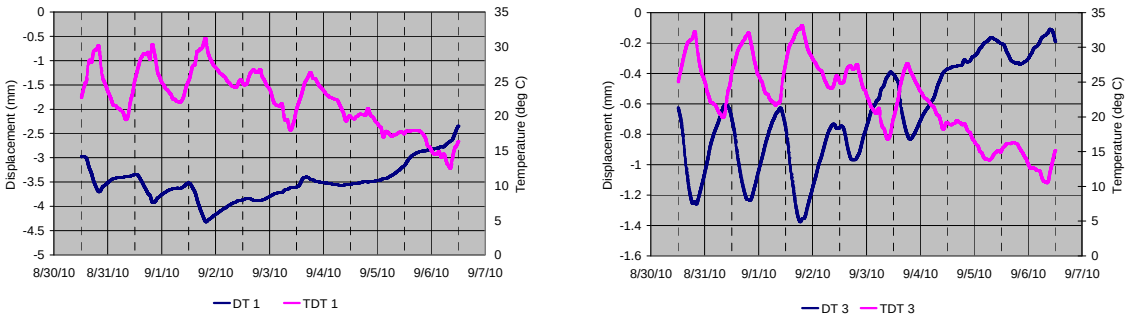


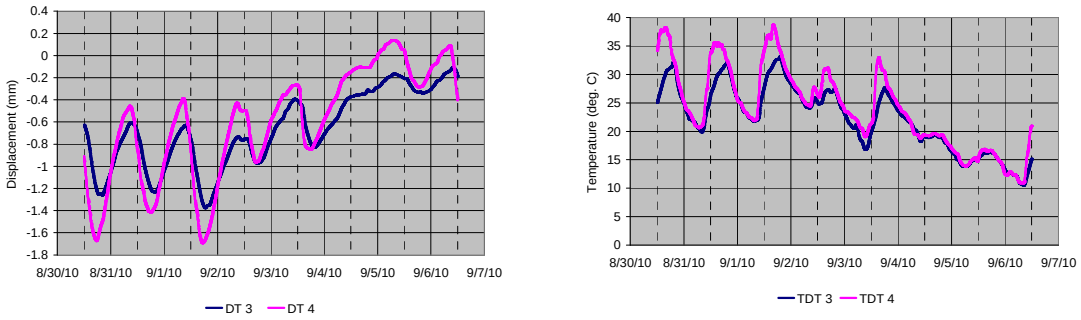
Figure 8. Displacement patterns in September 2010.

2.1.3 Data review

The data presented in Figures 6 through 8 clearly indicates that the change in displacement closely follows the change in temperature leading one to conclude that displacements recorded are temperature induced. In some instances, however, there is clearly identifiable time lag between the temperature change and the corresponding change in displacement. This can most likely be attributed to the fact that the temperature changes, due to change in ambient temperature or due to direct exposure to sunlight or shading effect from clouds, are measured almost instantaneously, whereas the concrete superstructure can take relatively longer time to undergo expansion or contraction.

Transducers DT 3 and DT 4 both measure displacement at the free end of the cantilever and theoretically should measure identical displacements. However due to the peculiar orientation of the bridge one side of the bridge gets greater exposure to the sunlight and undergoes greater thermal changes as shown in Figure 9.

Figure 9. Comparison of data pattern for DT 3 and DT 4 – (left) displacement and



(right) temperature

2.2 Effectiveness of monitoring

2.2.1 Sensor performance

The sensors performed effectively during the critical monitoring period and thereafter. During the latter part of monitoring four strain gauges and the lower tilt meter were buried under about 2 m layer of backfill. Special protective covers were installed in advance and the sensors continue to provide data. The daily and the seasonal temperature changes the buried sensors are significantly less.

2.2.2 System

The system performed as intended with minimal local or remote intervention. The temperature of the equipment enclosure and the backup battery voltage constantly monitored and was also incorporated into the alarm system.

2.2.3 Data communication

The data communication was generally satisfactory. Edmundston is located close to the US border and the local cellular communication is occasionally influenced by the presence of cellular communication towers on the US side. Loss of data communication was avoided by timely remote intervention.

2.2.4 Conclusion

The Structural Health Monitoring (SHM) system on Madawaska River Bridge was installed and operated for over one year. The system helped alleviate any uncertainties with regards to the stability of Pier 1 during construction in its immediate vicinity. This application has demonstrated that a well designed SHM system can a cost-effective risk management tool for the asset owners and engineers. Pier 1 and the completed power

channel are shown in Figure 10.

Figure 1. Pier 1 after completion of power channel.

2.2.5 References

Levesque, C., and McAfee, R., 2009. Geotechnical Stability Analysis - East Pier, Boucher Bridge, Edmundston, NB