Long-term monitoring of the Tall Piers of a Multi-span Beam Bridge Using a Network of Digital Inclinometers: First Results and Perspectives

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ABSTRACT

This paper presents the continuous, multi-sensor monitoring system installed on a multi-span beam bridge of the Athens toll-way (Greece) for capturing, analyzing and understudying its structural condition and, ultimately, for evaluating its structural integrity status. Particularly, the focus of this work is placed on field data acquisition and analysis of the tilt (inclination) sensor system mounted on the cap of the taller (> 17m) piers, used for extracting the pattern of the long-term, quasi static inclinations of the bridge complex and for constructing an envelope of typical safe operation. The tiltmeter monitoring system setup including raw data transfer, manipulation and pre-processing procedures are fully detailed. Moreover, the signal processing techniques, the data filtering types and statistical analysis tools developed are also discussed. From the data analysis obtained for the first 9½ months of continuous operation of the system the dynamic and static deformations of the bridge are evident. More specifically, the dynamic response of the structure due to heavy passing vehicles is apparent and in conformance to traffic records. Also, the daily and seasonal effects found in the data are consistent and in conformance with the variations in meteorological readings as well as with independent monitoring techniques, such as the displacements obtained using continuous Robotic Total Station (RTS) observations. Finally, a proposal for further analysis of the long-term, multi-sensor measurements combining structural modeling information towards structural integrity identification is also provided.

I. INTRODUCTION

Continuous monitoring of the static and dynamic behavior of bridges aims at capturing, analyzing and understanding their actual structural condition and integrity status. Sensor networks deployed on carefully selected bridge elements produce field data that facilitate the detection of changes that ,if significant, could be associated with deviations from the normal behavior, indicating developing faults affecting bridge performance (e.g. bearing capacity, stiffness, serviceability and durability) (Gikas 2012; Gikas *et al.*, 2016; Kaloop *et al.*, 2018). Furthermore, long-term monitoring serves the development of optimized maintenance strategies and damage rehabilitation policies aiming at reducing operational expenses in the service life of a structure.

Traditionally, various types of sensors have been used in bridge health monitoring ranging from those measuring strain and acceleration parameters to others capturing fine rotation and displacement effects (Moschas *et al.*, 2012; Kohut 2013; Piniotis *et al.*, 2016; Yigit and Gurlek, 2017). Recently, the rapid developments in sensor and communication technologies has made a shift towards integrated sensor networks and the adoption of advanced analysis tools suited for large volume data leading to new perspectives in structural monitoring (Seo *et al.*, 2016; Hussan *et al.*, 2018). At an implementation stage, however, except the numerous practical issues that one has to consider (excessive volume data handling, standardizing, cleaning, etc.), other fundamental concerns arise such as the detection, modeling and removal of meteorological and seasonal effects in the data, removal of dynamic incidents as well as the presence of measurement noise (Dai *et al.*, 2018).

This study deals with the set-up, the configuration and data analysis processes adopted for the continuous monitoring system installed on a girder bridge of the Athens toll-way, Greece, aiming at studying its dynamic and long-term behavior. Particularly, in this work the focus is placed on the digital inclinometer array used to capture the vertical inclinations of the tall piers and the results of the statistical analysis obtained for the first 9½ months of the system operation.

II. INCLINOMETER-BASED BRIDGE MONITORING

Inclination or tilt sensors are used to measure horizontal or vertical angles of slope (inclinations) of an object with respect to gravity's direction with high precision. Depending on particular tilt sensor type their working principle relies on different technologies; namely, the servo technology, the fluid filled capacitance and conductive / MEMS technology (Bihter 2010; Yigit *et al*., 2010). There are several types of inclinometers all suited for their own purposes. In bridge monitoring applications, inclinometers often are employed to record the deck settlements induced during static load testing operations. In this case converting the measured tilt angles to displacements can be a challenging task depending on required accuracy and the type, location and number of available tilt sensors (Olaszek, 2014; Shenton *et al*., 2015; Zhang *et al*., 2016). Notably, for the case of long span bridges, the method has an advantage compared to standard leveling techniques due to limitations in their operational distance.

Also, digital inclinometers are used to study the health status of a bridge through recording tilt variations over long times at critical locations of a structure. Usually, digital tilt sensors are mounted either at the bottom or at the top of the bridge piers to measure the fine rotation response of the structure.

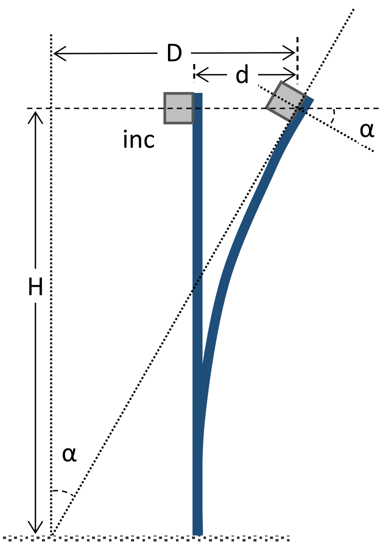

Figure 1. Shear effect on inclinometer observations

The method is usually employed as part of a monitoring program featuring a network of sensors placed at large, critical infrastructures bearing heavy traffic loads or bridges located at scour and/or earthquake-prone areas. One issue that needs particular attention when monitoring the top of a bridge pier is the translation of the measured tilt angle to displacement. As shown in Figure 1, converting the tilt angle to movement using a linear relationship of the rotation angle to the pier's height one ignores the non-linearity in the actual deformation of the structure introduced due to shear effects (Abu Sinena and Abu Sinena, 2017). However, the error imposed in this assumption for concrete, load-bearing structures still might be small.

III. BRIDGE DESCRIPTION AND MONITORING PROGRAM

A. *Test Bridge*

The bridge under investigation is the "Elefsina-Lamia" roadway overpass of *Attiki Odos SA* closed toll motorway servicing the greater metropolitan area of Athens, Greece. The study bridge forms part of the Metamorfosi interchange of Attiki Odos with the National Highway from Athens to Thessaloniki.

Figure 2. Test bridge. The inclinometer locations on the piers and ground are circled in yellow and purple.

B. *The Monitoring Program*

The monitoring program aims at studying the long-term variations (i.e., fine displacements and rotations) in the geometric setting of the three tallest piers (M6, M7, M8) and at selected parts of the bridge girder in between the piers (Figure 2). Also, it includes studying the vibration response of the central (tallest) pier (M8) to compute critical parameters related to the dynamic performance of the structure and their correlation to seismic effects and operational loads.

The bridge monitoring system consists of two parts. Firstly, a network of digital inclinometers and topographic prisms installed on the three tallest piers of the overpass to capture the long-term variations in the geometry of the structure. Secondly, a combination of two high sensitivity accelerometers installed perpendicularly at the tallest pier (M8) and GBMI (Ground-based Microwave Interferometry) measurements undertaken at measurement campaigns along its full length to study the vibration parameters of the pier.

IV. INCLINOMETER ARRAY MONITORING SYSTEM

A. *Monitoring System setup*

Regarding the tilt sensor network, four dual-axis digital inclinometers (*Nivel 220, ±0.0047 mrad; Leica Geosystems*) were installed at the cap of each of the three piers (see Figure 3) and the remaining one at a nearby location at stable ground to serve as a reference unit. The inclinometers were configured to operate in a chain mode through GeoMOS® monitoring software. In addition to in-house meteorological sensors embedded in the tilt sensors, a high quality meteorological sensor (*HMP 110; Vaisala, measurements of:* ambient temperature, atmospheric pressure and humidity) was also installed on pier M8. Data are recorded continuously and transferred via internet to the NTUA for processing and analysis. Today (Dec. 2018) the system has completed 9½ months of continuous operation. Sensor data are filed, tagged and transferred on a daily basis from a local PC placed in the test site area to a central computer located at the NTUA Network Operations Center (NOC) for storage and further processing. On the occasion of a loss of connection between the two computers, data are stored locally and are transferred to the NTUA computer soon after the connection is restored. Once raw data have been retrieved from the NTUA NOC center and before any pre-processing operation starts, raw data are converted from *ASCII* to binary type for more efficient handling in subsequent analysis steps.

V. STATISTICAL ANALYSIS AND SIGNAL PROCESSING TECHNIQUES

A. *Examination of raw data timeseries*

In order to study the operational efficiency and overall performance of the monitoring system raw data recording was set at a sampling rate of 60 s during the entire trial period, scheduled to increase at 15 s at rush hours (from 07.00 to 10.00) to enable a more detailed view of the response of the structure at busy traffic periods. For every inclinometer, its x axis orientation is parallel to the respective pier's cross section short side (parallel to the overlying bridge deck axis), while, the y axis orientation is parallel to the respective pier's cross section long side (transversal to the overlying bridge deck axis). Figure 4a shows the timeseries of raw tiltmeter data captured on pier M6 along the x-axis for a period of 9½ months.

Figure 3. Digital inclinometer enclosure deployed on the cap of pier M6

The first thing to note from this plot is a long-term, quasi-static pattern that seems to follow a cyclic period of more than 9½ months, suggesting seasonal effects on the response of the structure. Moreover, the highly noisy character of the recorded tilt variations is attributed to operational loads (heavy vehicles) that induce instant but excessive dynamic vibrations on the structure, masked by the low sampling frequency of inclination sensors.

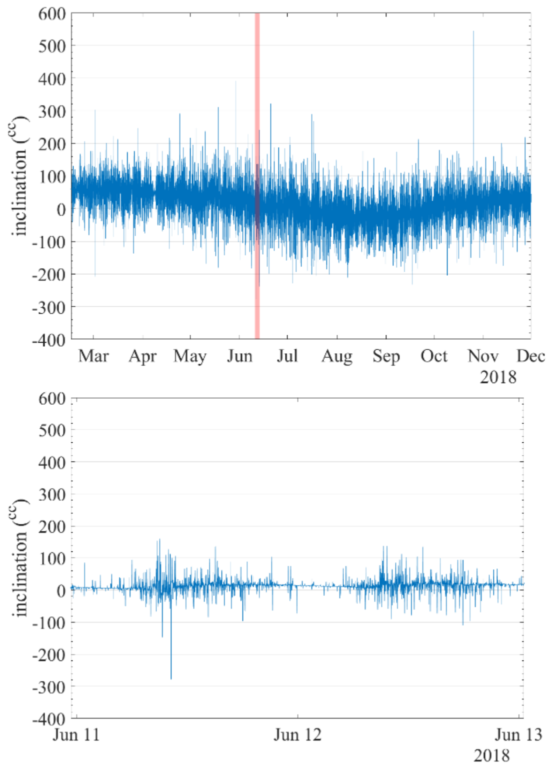

Figure 4. *a)* Timeseries of raw inclination data (x-axis) captured on pier M6 for a period of 9 ½ months and b) for a period of two consecutive days

At a microscopic scale (see Fig. 4b), the tilt recordings exhibit a short term cyclic behavior of a 24-h period representing the response of the structure to temperature variation effects. Moreover, as expected, the inclinometer signal gets less noisy during the after midnight hours, when the number of over-passing vehicles decreases, leading to sparse incidence of peaks. From the same plot, one can also identify the traffic rush hours identified by the extended periods of excessive tilt values, while at all other times vehicle passages are random, resulting in only individual peaks.

Analysis of the raw data recorded on piers M7 and M8 results in similar conclusions. For instance, Figure 5 shows the tilt recordings captured along the y-axis at the top of pier M8 spanning a two-day period, starting at midnight Saturday (Oct. 27) to Sunday (Oct. 28), ending on Monday night (Oct. 29). Comparing the signals obtained on Sunday (weekend day) against those captured on Monday (working day), the latter is by far noisier due to the large number of vehicles passed through the bridge.

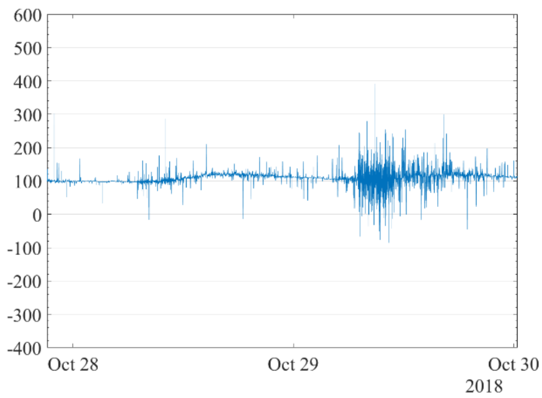

Figure 5. Raw inclination data for a two successive-day period, one weekend day and one working-weekday

B. *Statistical analysis - Signal processing techniques*

In order to unveil the quasi-static behaviour of the piers, inclinometer data have to be properly filtered.

The signal processing techniques adopted (Figure 6) are as follows:

a) Signal downsampling: By closely examining the signals, a resampling period of 10 min is adopted.

b) Peak removal: A filter that removes the peaks that differ more than three standard deviations (±3σ) from the median of a predefined window is applied, replacing them with that median.

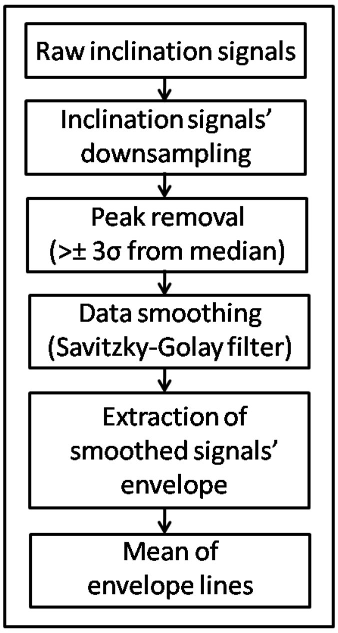

Figure 6. Signal processing techniques adopted

c) Data smoothing: The data is further smoothed through a Savitzky–Golay filter that fits successive sub-sets of adjacent data points with a low-degree polynomial, using linear least squares. This is a low-pass filter that is adopted due to its zero phase property, according to which the primary signals are not shifted in time.

d) Further data smoothing: Two envelope lines constructed from the previously smoothed signal's maximum and minimum peaks, respectively, are calculated. Then, the mean of these lines is computed.

Figure 7 shows the raw inclinometer data over imposed by the corresponding filtered values. The final signal depicts the seasonal variations of the pier's inclination.

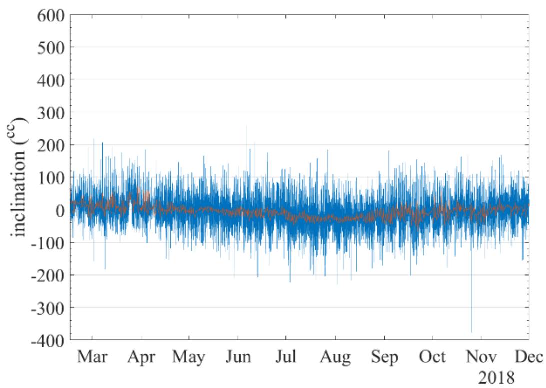

Figure 7. Timeseries of raw and filtered inclination data of pier M7 (x axis) for the 9½ months period

VI. DATA ANALYSIS AND DISCUSSION

The timeseries of the filtered inclination signals with the environmental temperature timeseries clearly suggests the strong correlation between the ambient temperature and the daily quasi-static response of the structure (figure 8).

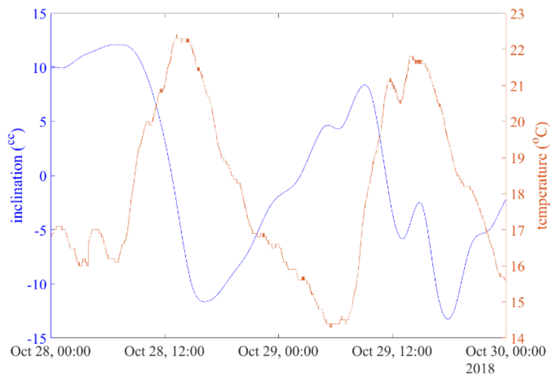

Figure 8. Timeseries of filtered inclination data of pier M8 (y axis) and environmental temperature

It is evident that the structure reacts consistently to the daily temperature changes after a time-lag of about 3 hours, reaching its daily peak inclination values in response to the occurrence of temperature peaks. Taking into consideration the relative orientation of the cross-section of the pier and the direction of the sun movement, it becomes obvious that the structure starts inclining towards south from the early morning hours until the late afternoon and does the opposite for the remaining day.

The bridge deck under investigation is a single lane road that on weekday morning is occupied by heavy passing vehicles that in rush hours move slowly and occasionally remain stationary. This results in instances of occupation of the bridge-deck with stopped vehicles, along its full length. Figure 9 illustrates the apposition of the filtered inclination signals with the occupation of the bridge deck (as a percentage for every 5 min duration time) for the y-axis of the inclinometer in M8 pier.

This plot shows a two-day period, starting at midnight Saturday (July 15) to Sunday (July 16), ending on Monday night (July 17). From figure 9 it is apparent that, the occupation of the bridge increases during rush hours in the working day (Monday), which is due to the additional weight of the stopped vehicles, suggesting an increase in the values of the pier inclination observed, as opposed to the inclinations for the weekend day (Sunday).

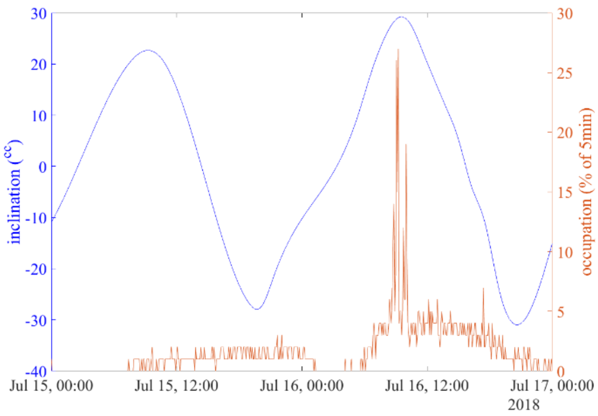

Figure 9. Timeseries of filtered inclination data of pier M8 (y axis) and bridge deck occupation by stopped vehicles

From figures 8 and 9 becomes evident that the "driving" cause of the pylons' daily inclination variation is the alteration of the ambient temperature and to a much lesser extent, the additional load of the stationary vehicles at the overlying bridge deck during the rush hours.

Furthermore, Figure 10 shows the timeseries of x and y axes filtered inclination data of all inclinometers along with the timeseries of temperature data for the 9½ months period of continuous operation of the system.

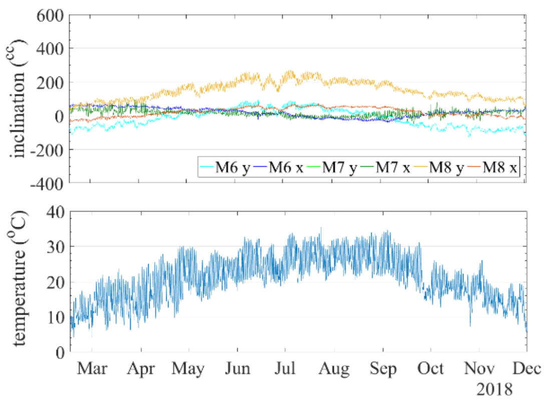

Figure 10. Timeseries of filtered inclination data of all inclinometers versus environmental temperature timeseries

Both axes' signals of all inclinometers exhibit the same pattern driven perhaps by the temperature variations, i.e. signals and temperature exhibit their annual peak in July and seem to have a cyclic behavior, starting from a value and descending from winter to summer months, phenomenon that is reversed from the hottest month (July) and then. Moreover, in order to analyze this behavior better, the mean x axis inclination value for every month is calculated using the filtered signal data and plotted against the respective y axis mean value for each pier. The resulting plots for the three piers are shown in figure 11.

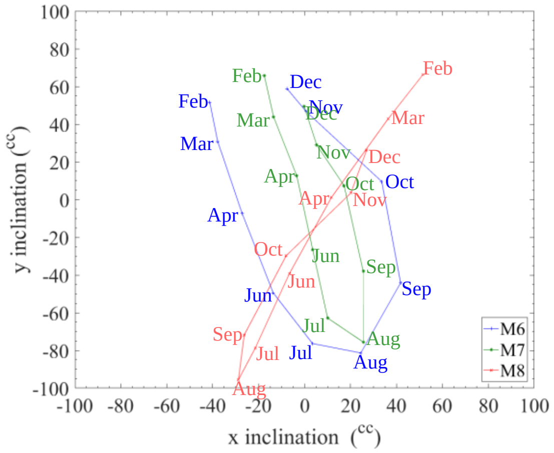

Figure 11. x vs y averaged filtered inclination data of the three piers

Close examination of the inclination plot for pier M6 in figure 11, reveals that the range (peak to peak) inclination on the y axis is approximately 2 times greater than the respective inclination on x axis. This can be possibly explained due to the linear geometry of the overall structure (i.e. the over-passing road connecting piers M6 to M8 makes the rotation along the x inclinometer axis (along the road deck) more restricted in comparison to the rotation on the y axis (across road deck), which develops more degrees of freedom). Additionally, the pier's M6 plot (x vs y inclination) reveals an annual cyclic inclination behavior that exhibits its y axis extreme values at the hottest (July) and as it appears, at the coldest month, while the x axis extreme values are observed by the end of winter (February) and the end of summer (August). These conclusions also apply to piers M7 and M8 inclination data, except that for pier M7 the range (peak to peak) inclination on the y axis is approximately 4 times greater than the respective inclination on x axis, probably because of the fact that on top of it there is a deck assembly joint (i.e. the pier is not attached to the overlying road deck) in contrast to the other two piers that are monolithic (i.e. they constitute a body with the deck). It is also worth mentioning that the range (peak to peak) inclination on the y axis of all three piers is of the same order (140 cc) and that the x vs y inclination plots of piers M6 and M7 exhibit the same orientation.

Moreover, all piers seem to bend towards South from the cold winter time to the summer, reaching a mean inclination peak in July, and then they start bending back towards North. As it can be seen in figure 11, the annual bending pattern for the piers M6 and M7 is identical, featuring an anti-clockwise trajectory from February to November, whereas the pier M8 exhibits a linear trajectory. These conclusions have also been validated by the results of an RTS (Robotic Total Station) of three monitoring sessions (January, June and November). Regarding piers M7 and M8, the RTS results show complete compatibility with the respective inclinometer data. On the contrary, for pier M6, the results of RTS and inclinometer differ and the cause is under investigation. The RTS results are depicted on plots that are also included in figure 12, after having maintained the same local pier axis orientation. These results concern the monitoring of three RTS prisms located at the top of the piers, co-located with the respective inclinometers.

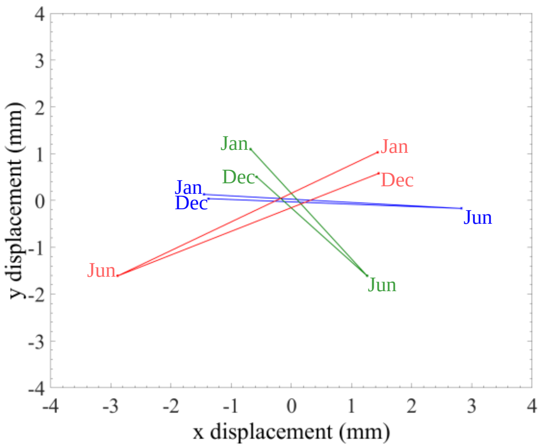

Figure 12. x vs y averaged displacement data of the three piers

The combined plots (inclination and displacement) for the three piers are further positioned individually on a map of the piers and the overlying road section for better interpretation (figure 13), from which a cyclic quasi-static structural behavior of a period that seems to be annual for each of the three piers is depicted.

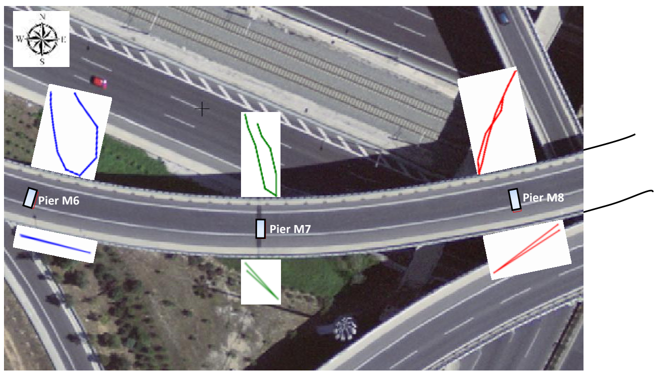

Figure 13. x vs y inclination and displacement data of the three piers *on a map*

VII. CONCLUSIONS AND OUTLOOK

Analysis of the continuous tilt-angle data obtained for the first 9½ months of continuous operation reveals the bridge response to daily and seasonal temperature cycles indicating a pattern of normal quasi-static structural movement, which will be used to construct an envelope of the typical safe operation.

These findings are in conformance with the independent results derived from a number of campaign-based RTS (robotic total station) monitoring sessions suggesting the correctness and feasibility of the tilt sensor setup and the signal processing / statistical analysis tools adopted.

The future goal of the monitoring project is to assess the long term structural behavior of the bridge piers by continuously monitoring their inclinations, along with environmental parameters such as air temperature, relative humidity, pressure and accumulative rainfall. This will be achieved by constructing statistical models to depict the relationship between the inclination data and mainly the ambient temperature that seems to govern the piers' structural behavior. Once sufficient amount of data is available, the models will be adjusted and will serve as predictors of the piers structural response and therefore as indicators of their structural integrity.

References

Abu Sinena, H., Abu Sinena I.M. (2017). Dynamic Monitoring of Tall Buildings. *The Int. J. of Engineering and Information Technology*, Vol. 4, No.1

Bihter E. (2010). Evaluation of High-Precision Sensors in Structural Monitoring. *Sensors*, Vol. 10, No. 12.

Breuer P., Chmielewski T., Górski P., Konopka E., Tarczynski L., The Stuttgart TV Tower − displacement of the top caused by the effects of sun and wind, *Engineering Structures*, Vol. 30(10), 2008, 2771-2781.

Dai, G., Tang Y., Liang L., Yang L., Chen Y.F. (2018) Temperature Monitoring of High-Speed Railway Bridges in Mountainous Areas. *Structural Engineering International*, Vol. 28, No. 3.

Gikas V. (2012). Ambient Vibration Monitoring of Slender Structures by Microwave Interferometer Remote Sensing. *J. of Applied Geodesy*, Vol. 6, No. 3-4.

Gikas V., Karydakis P., Mpimis A., Piniotis G., H. Perakis (2016). Structural Integrity Verification of a Cable-stayed Footbridge Based on FEM Analyses and Geodetic Surveying Techniques. *Survey Review*, Vol. 48 No. 346.

Hussan M., Kaloop M.R., Sharmin F., Kim D. (2018) GPS Performance Assessment of Cable-Stayed Bridge using Wavelet Transform and Monte-Carlo Techniques. *KSCE Journal of Civil Engineering*, Vol. 22, No. 11.

Olaszek, P. (2014). Deflection Monitoring System Making Use of Inclinometers and Cubic Spline Curves. In: *Bridge Maintenance, Safety, Management and Life Extension*, by Airong Chen, Dan Frangopol, and Xin Ruan, CRC Press

Kaloop M.R., Yigit C.O, Hu J.W. (2018) Analysis of the Dynamic Behavior of Structures Using the High-rate GNSS-PPP Method Combined with a Wavelet-neural Model: Numerical simulation and experimental tests. *Advances in Space Research*, Vol. 61. No. 6.

Kohut P., Holak K., Uhl T., Ortyl Ł., Owerko T., Kuras P., Kocierz R. (2013). Monitoring of a Civil Structure's State Based on Noncontact Measurements. *Structural Health Monitoring*, Vol. 12, No. 5-6.

Moschas F., Psimoulis P., Stiros S. (2012). GPS/RTS Data Fusion to Overcome Signal Deficiencies in Certain Bridge Dynamic Monitoring Projects. *Smart Structures and Systems*, Vol. 12, No. 3-4.

Piniotis G., Gikas V., Mpimis A., Perakis H. (2016). Deck and Cable Dynamic Testing of a Single-Span Bridge Using Radar Interferometry and Videometry Measurements. *J. of Applied Geodesy*, Vol. 10, No. 1.

Seo J., Hu J.W., Lee J. (2016). Summary Review of Structural Health Monitoring Applications for Highway Bridges. *J. of Performance of Constructed Facilities*, Vol. 30, No. 4.

Shenton H., Fernandez M., Ramanna N., Al-Khateeb H. (2015). Structural Health Monitoring of a Cable-Stayed Bridge: Using Tiltmeter Data to Determine Edge Girder Deflections. 7th Int. Conf. on Structural Health Monitoring of Intelligent Infrastructure, At Torino, Italy

Tamura Y., Matsui M., Pagnini L.-C., Ishibashi R., Yoshida A., *Measurement of wind induced response of buildings using RTK-GPS*, *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 90, 2002, 1783-1793.

Yigit C.O., Li X., Inal C., Ge L., Yetkin M. (2010). Preliminary Evaluation of Precise Inclination Sensor and GPS for Monitoring Full-scale Dynamic Response of a Tall Reinforced Concrete Building. *J. of Applied Geodesy*, Vol.4.

Yigit, C.O., E. Gurlek (2017). Experimental Testing of Highrate GNSS Precise Point Positioning (PPP) Method for Detecting Dynamic Vertical Displacement Response of Engineering Structures. *Geomatics, Natural Hazards and Risk*, Vol. 8.

Zhang W., Sun L.M., Sun S.W. (2016). Bridge-Deflection Estimation through Inclinometer Data Considering Structural Damages. *J. of Bridge Engineering*, ASCE, Vol. 22, No. 2.