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Monitoring of Bridge Deformation Using GPS Technique

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Abstract

Tianjin Yonghe Bridge is one of the important infrastructures in China where it serves as the crucial links in the transport network. Monitoring and maintenance of this bridge are essential tasks in prolonging its life. In this paper, GPS system was used for deformation data collection. Two analytical methods namely; Kalman Filter (KF) and Parametric Least Square (PLS) were used for the adjustment of these data. The analysis of test results indicate that: (1) the traffic loads are the main factor affects bridge damage, (2) after ten months of traffic opening, the south tower of bridge was returned to its original case, and (3) the maximum deformation was pronounced 48.2 m far from the beginning abutment after six months of bridge opening.

Keywords: *monitoring, bridge, GPS, deformation, kalman filter, parametric least square*

1. Introduction

Bridges are one of the important infrastructures in the national economy, which are considered as the crucial links in transport network. Many bridge failures caused by normal or abnormal loadings. Monitoring the bridge deformation is the vital task in bridge maintenance and management. The process of implementing a damage identification strategy for aerospace, civil and mechanical engineering infrastructure is referred to as Structural Health Monitoring (SHM). Damage is defined as changes in the material and/or geometric properties of these systems, including changes in the boundary conditions and system connectivity, which adversely affect the system's performance (Farrar *et al*., 1988). One of the most common bridges nowadays in the world is suspension bridge. A suspension bridge usually has two kinds of distinct deformations long and short term deformation. The long-term deformation caused by foundation settlement, bridge deck creep and stress relaxation, and the short-term dynamic motion of the bridge, such as those induced by wind, temperature, tidal current, earthquake, and traffic. Unlike the long-term bridge deformation, which is irrecoverable, the latter deformation is called a deflection since the deformable object will recover to its original status with the release of loadings, unless under an extreme loading, permanent damage or deformation occured (Meng, 2002). Global Positioning System (GPS) has been successfully used to measure displacements of oscillating flexible civil engineering structures such as long suspension bridges and high-rise buildings, and to derive their modal frequencies, usually up to 1 Hz, but there is evidence that these limits can be exceeded using high frequency GPS receivers (Panson *et al*., 2008; Ueno *et al*., 2003).

Many monitoring techniques have been applied to some bridges that are under construction or have been built. For example, the Automatic Data-Acquisition System, which was set up on Skarnsunder diagonal cable stayed bridge that spans 530 m in Norway, can monitor wind vibration, acceleration, gradient, strain, temperature and the displacement for the bridge automatically (Yu *et al*., 2006). Another technique "the wind and the structure health monitor system" had been installed on Qingma Bridge that span 1377 m in Hong Kong for monitoring the safe status of the entire bridge (Yu *et al*., 2006). The sampling frequency of GPS receiver can reach to 20 times per second, while the location precision can approach 5-10 mm. So, GPS can be used in the displacement monitoring of large structures (Azar *et al*., 2008). The threshold of 5-10 mm has been documented mostly on the basis of experiments in which the known oscillatory movement of a certain device was compared with that recorded by a GPS receiver mounted on this device in comparison to another nearby GPS receiver fixed on stable ground (Panson *et al*., 2008). Real-time kinematics (RTK) GPS technology is an important development to aid continuous deformation monitoring, where the timely detection of any deformation is critical (Ince *et al*., 2000). Monitoring the bridge deformation with GPS has following advantages (Yu *et al*., 2006):

1. GPS measurements depend on the signals radiated from satellites in the space. Once receiving the signals from five

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or more observed satellites, RTK differential positioning can be realized. The visible between each station is not necessary, and the observed data in each station is independent.
2. GPS can be used in all-time monitoring, even under inclement weather.
3. The monitoring by GPS is automatic. Capturing satellite, receiving signal, and RTK differential positioning can be completed by GPS receiver. The three-dimensional coordinates measured can be transmitted into the center (monitoring server) to perform the bridge security analysis directly.
4. The monitoring time by GPS is less, but the precision gets much higher. The output rate of GPS/RTK positioning may reach 10-20 Hz.

For analyzing the signals of GPS, a preprocessing should be done first to delete noises and extract useful signals. Wavelet analysis is a strong tool to eliminate noises according to the noise characteristics (Yu *et al*., 2006). The integration of GPS and inertial sensors is typically accomplished through using Kalman Filter (KF) (Kaplan *et al*., 2001; Ince *et al*., 2000). KF, introduced in 1960 by Dr. R. E. Kalman (Haykin, 2001), is a statistical technique that combines the statistical nature of system errors with system dynamics, as represented as a state space model, to achieve best estimation of the system state. The KF is considered an optimal filter (Kaplan *et al*., 2001). The KF and Parametric Least Square (PLS) are two types of wavelet analysis used in wide area of GPS applications

However, the focus of this research is:
1. To use the PLS with KF in GPS data processing
2. To determine the deformation and its time of happening
3. To find out the reasons that affect bridge damage

2. Bridge Description

The Tianjin Yong Highway Bridge is a cable-stayed bridge connecting between Tianjin and Han Gu cites, and crosses over the Yong River, in China. This bridge was constructed by prestressed concrete in December 1987 (Fig. 1), closed in October 2006 because of cracks over mid span and opened in August 2007 after rehabilitation. The whole bridge has four lanes with the total length of 510.00 meters, and main span of the bridge is 260.00 meters.

For safety assurance, a sophisticated long-term structural health monitoring system has been designed and implemented by the Research Center of Structural Health Monitoring and Control of Harbin Institute of Technology to monitor loads and response of the bridge. The structural health monitoring system for the Yonghe Bridge comprises a data acquisition and processing system with a total of approximate 179 sensors, including accelerometers, strain gauges, displacement transducers, anemometers, temperature sensors, weigh-in-motion sensors and three GPS's. The GPS was permanently installed on the two tower tops of the bridge and bank near the bridge, as shown in Figs. 1 and 3.

Generally, for the cable-stayed bridges and other large-scale buildings, their inherent structure vibration has a lower frequency of 0.1-10 Hz due to their huge mass (Yu *et al*., 2006, Azar *et al*., 2008).

3. Information of GPS and Data Collection

To provide a continuous mapping of the bridge motion under loads, a kinematic GPS survey with data sampling rate of 20 Hz, the elevation angle of receivers is 13º, and at least 9 satellites as shown in Fig. 2, were adopted. For these reasons, three GPS receivers were setup: two on the top of the towers (Fig. 1) and another as a reference station on stable ground near the bridge as shown in Fig. 3, 2002 and 2001 denote northern tower (N.Tower) and southern tower (S.Tower), respectively. The positioning of receivers was related to WGS84 as shown Fig. 3.

The GPS observations are real time kinematic (RTK) with differential GPS (DGPS) system. The receivers are LEICA GMX902 antenna (24 channel L1/L2 code and phase, 20 Hz data rate, SmartTrack technology for high precession, solid and small, water resistance (IP67) anti vibration, accuracy of 1 mm + 0.5 ppm (horz.); 2 mm +1 ppm (ver.)) and pre-processed data using the software GPS Spider 2.1. The coordinate components for each observation epoch are derived (http://www.gnss.si/images_1/GMX902%20Flyer_en.pdf). Hence, the time sequences of positions for each station located on the bridge were generated. More over, hourly based corresponding atmospheric data as well as traffic volume statistics given were collected.

Two-rover observation stations were considered along the bridge in two tower of bridge, every rover station is observed for 24 hr, the number of data collection are 72000/hr, and each epoch is corrected with the base station. GPS device must be set up

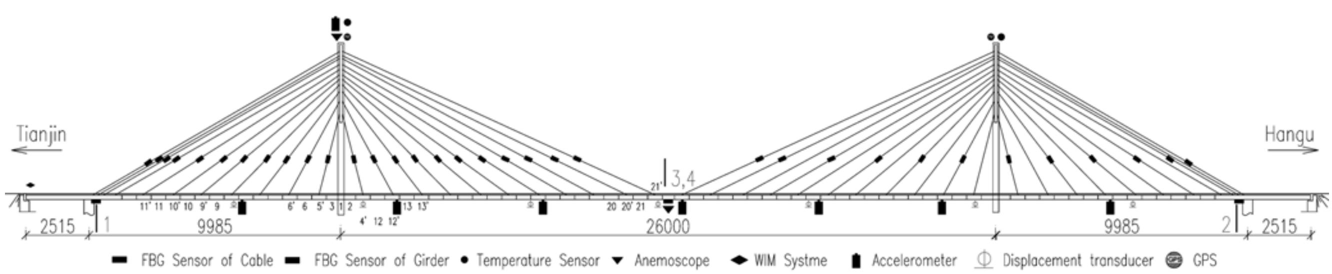


Fig. 1. Elevation and System of Health Monitoring of Tianjin Yonghe Bridge

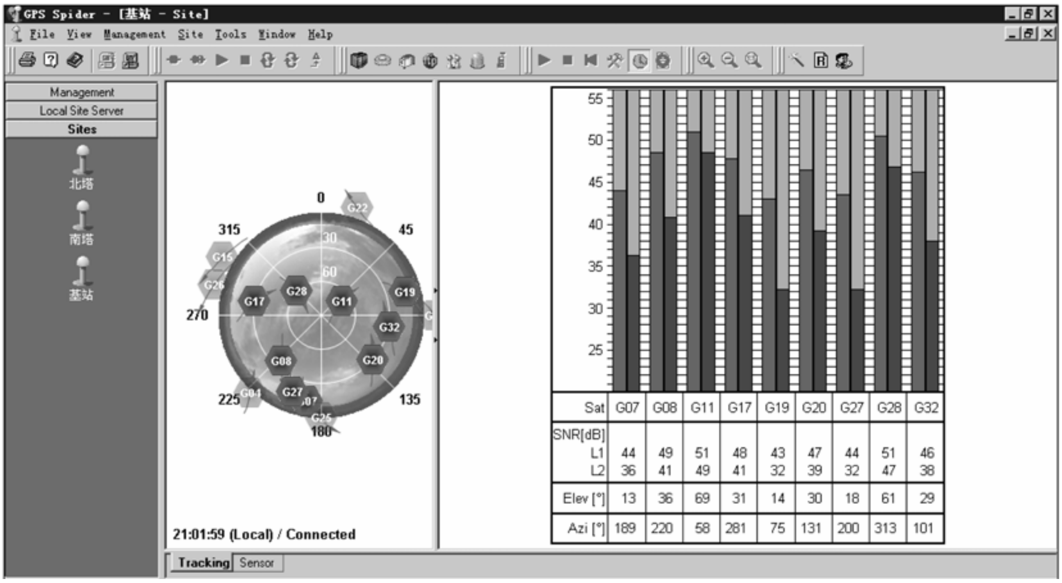


Fig. 2. The Number of Satellite and Elevation Angle of Receivers

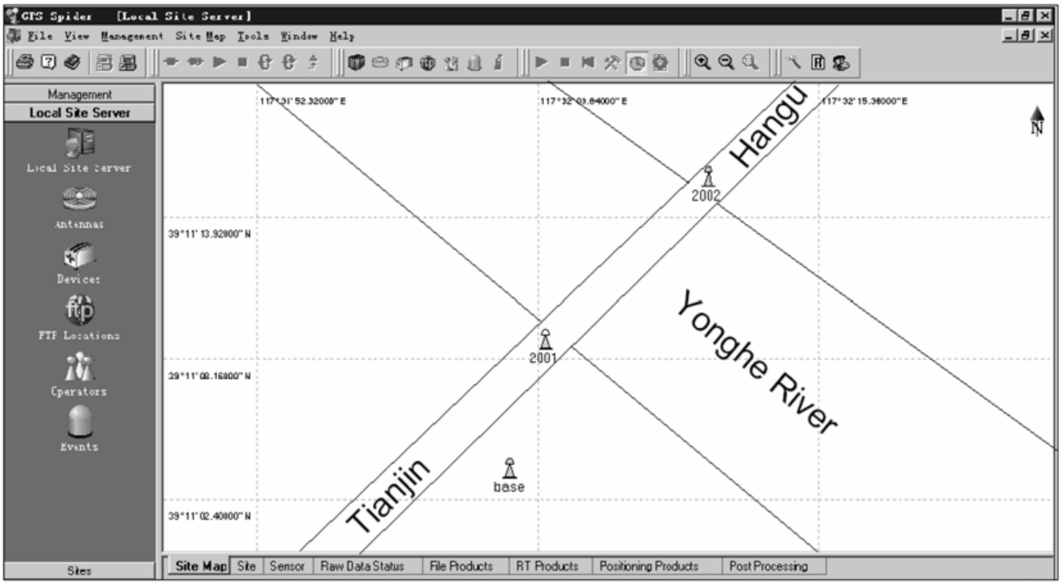


Fig. 3. GPS Dynamic Monitoring Scheme

carefully in order to give the appropriate data. Antenna settings must be checked and log on static mode must be turned on in tracking settings of the GPS device. So, the base station is corrected then each epoch of observation is corrected relative to its related base station. The observation time of base station should be corrected when it's more than that of rover. When all the rover observations are corrected, the data would be compared depending on each epoch of observations (Azar *et al*., 2008). GPS coordinates are formed in WGS84 format, which is considered as global degree format. The ellipsoidal coordinates (WGS84-Datum) of two towers are shown in Fig. 3. Using Eq. (1), the local coordinates of bridge for the two stations were converted to Cartesian coordinates and the results are summarized in Table 1.

Table 1. The Local Cartesian Coordinates of Bridge Towers

Tower	*X*-coordinate	*Y*-coordinate
Southern	4337438.924	500401.024
Northern	4337438.925	500662.027

All values in (m)

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_T = M * \begin{bmatrix} 1 & +R_Z & -R_Y \\ -R_Z & 1 & +R_X \\ +R_Y & -R_X & 1 \end{bmatrix} * \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_S + \begin{bmatrix} dX \\ dY \\ dZ \end{bmatrix} \quad (1)$$

The parameters are commonly referred to define the transformation "from source coordinate system to local coordinate system," where by (X_S, Y_S, Z_S) are the coordinates of the point in the WGS84 and (X_T, Y_T, Z_T) are the coordinates of the point in the local coordinate system of bridge. (dX, dY, dZ): Translation vector, to be added to the point's position vector in the source coordinate system in order to transform from source system to target system; also: the coordinates of the origin of world coordinate system in the target coordinate system. (R_X, R_Y, R_Z): Rotations to be applied to the point's vector. M: The scale correction to be made to the position vector in the source coordinate system in order to obtain the correct scale in the target coordinate system. $M=(1+dS*10^{-6})$, whereby dS is the scale correction expressed in parts per million (http://posc.org/ Epicentre.2 _2/Data Model/ Examplesof Usage/eu_cs.html.).

Fig. 4 shows sample of the observed environment effects on the tower and bride. These are the wind speed and wind direction respectively.

The average minimum temperature in Tianjin Yonghe bridge location is -3ºC in December and January whereas the average maximum temperature is 25ºC in August. The minimum record temperature is -13ºC in January and maximum record temperature is 30ºC in August.

$$\delta = \alpha \cdot \Delta T \cdot H \tag{2}$$

As indicated in Table 2, the deflections in the deck and the two bridge towers due to temperature affects are not very large.

Table 2. Deflection in Tower and Deck due to Temperature

Property	Value
Coefficient of thermal expansion, α	12×10^{-6}/ºC
Maximum temperature	30ºC
Minimum temperature	-13ºC
Change in temperature, ΔT	43ºC
Length of the tower, H	62.50 m
Length of the deck, L	260.00 m
Deflection in tower, δ	0.0323 m
Deflection in deck, δ	0.1342 m

Collection time series GPS data were carried out from 11.00 AM to 2.00 PM local time on June 2007 to June 2008, where the traffic loads, temperature, and wind have more effects on bridge. This present study, selected the south tower to study deformation, is comparison between the data every month, and discuses the reason of the movements.

4. Data Analysis

Transformation of GPS observations from global coordinates to local coordinates of bridges is shown in Fig. 5. To transform the coordinates to local axis used Bursa-Wolf transformation method. This transformation is given various names throughout the geodetic literature, such as three-dimensional similarity, three-dimensional conformal, seven-parameter transformation Helmert. This involves an origin shift in three dimensions, a rotation about each axis, and a change in scale, which is usually expressed in parts per million (ppm). The process can be simplified when using

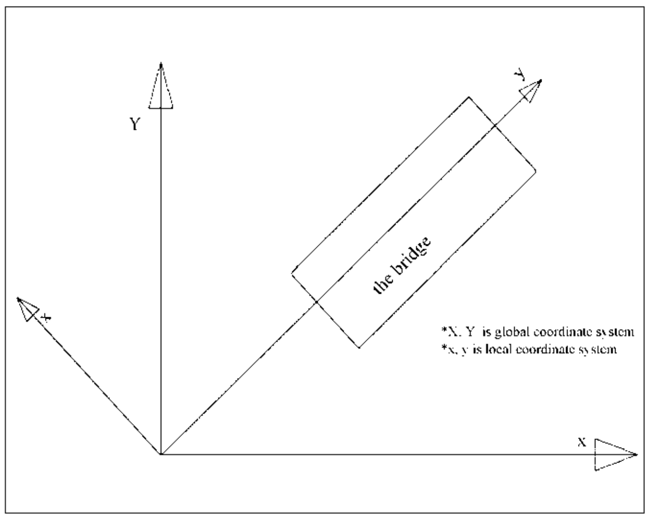
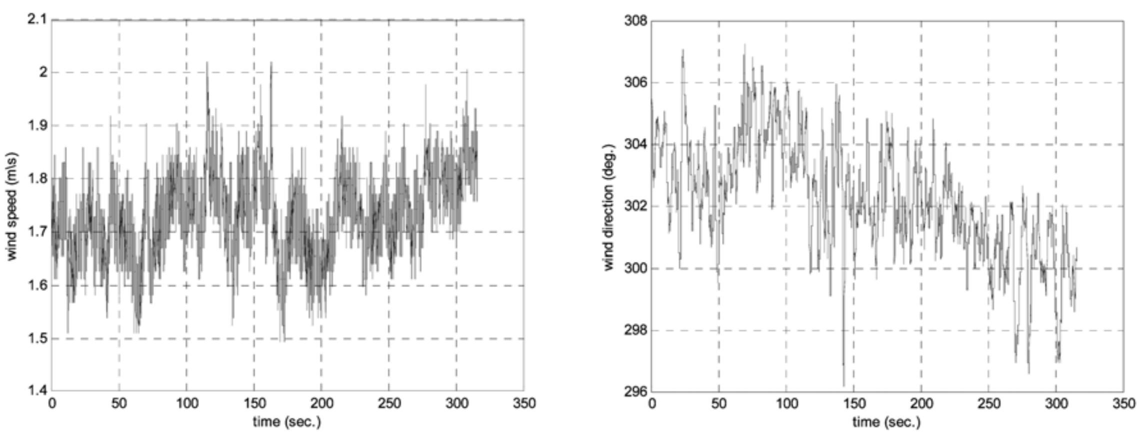


Fig. 5. The Coordinates System of the Study Bridge



(a) **(b)**

Fig. 4. The Sample of Environment Data Observed (a) Wind Speed, (b) Wind Direction

small axial rotations by producing a combined rotation matrix (Harvey, 1986).

The analysis in this study was based on the data collection in the X and Y-directions, since the movement in these directions are greater than this obtained in Z-direction, thus we declined the data in Z-direction. In GPS observations two adjustment steps should be considered, these are KF and PLS. This adjustment was performed by inserting a subroutine in the Matlab software program as described in the following paragraphs.

4.1 KF Method

KF is now used in a wide variety of GPS applications, and not restricted to moving platform scenarios (Mohinder *et al*., 2007). In particular, KF algorithms for the resolution of the cycle ambiguities and the detection and correction of cycle slips have been developed, and continue to be investigated (http://www.gmat.unsw.edu.au/snap/gps/gps_survey/principles_gps.htm). To express the kinematic behavior of the system between two epochs, a kinematic model is defined by a linear relation between the system parameters at two different epochs (Haykin, 2001):

$$FX_0 + W = X \tag{3}$$

Where: X, X_0 are the state vector at time t and t_0 respectively, F is the transition matrix; and W is the system noise. According to the propagation law of variance, and assuming X_o and W are independent, the variance-covariance matrix of the prediction estimate is:

$$Q_{XX} = FQ_{X0X0}F^T + Q_{WW} \tag{4}$$

Where: Q_{X0X0}, Q_{WW} are the variance-covariance matrix of state vector at t_0, variance-covariance matrix of system noise respectively. X- Parameter can be estimated as:

$$X^* = X + K(Y - AX) \tag{5}$$

Where: Y is observed vector, A is measurements matrix and K is Gain-matrix, calculated by:

$$K = Q_{XX}A^T(AQ_{XX}A^T + Q_{ll})^{-1} \tag{6}$$

Where: Q_{ll} is the variance-covariance matrix of observation vector. To calculation the variance-covariance matrix of the estimated vector:

$$Q_{X^*X^*} = (I - KA)Q_{XX} \tag{7}$$

However, it should be mentioned herein that the obtained results from GPS Spider 2.1 program were used in the KF analysis method.

4.2 PLS Methods

This method of adjustment makes used observation equations, where observables are expressed as a function of some or all of the parameters, in the general form $l = f(X)$. To satisfy this relation, actual observations need to be adjusted (http :// www. gmat. unsw. edu. au/ snap/ gps/ gps_ survey/principles _ gps.htm.; Elsheimy, 2001). The linearization of the relation is performed about an approximate set of parameters X_o.

$$\left.\begin{aligned} l - V &= f(X_o) \\ l - V &= f(X + \delta X) \\ l - V &= f(X_o) + H\delta X \\ (l - f(X_o)) - V &= H\delta X \end{aligned}\right\} \tag{8}$$

Where: δX are the corrections to the approximate parameters and **H** is the design matrix containing the partial derivatives of the observations with respect to the parameters. The expression in brackets is the approximate residual, and is denoted by V_o. The variance-covariance matrix Q_{ll} of the observations is assumed known. As V_o differs from l only by a constant, it has the same stochastic behavior. The computational procedure therefore is:

$$V_o - V = H\delta X \text{ with weight matrix } P = Q_{ll}^{-1} \tag{9}$$

Solution for the parameters:

$$\delta X^\wedge = (H^TPH)^{-1} H^TPV_o \tag{10}$$

With variance covariance matrix of parameters:

$$Q_{x^\wedge x^\wedge} = (H^TPH)^{-1} \tag{11}$$

However, it should be mentioned herein that the obtained results from KF method were used in the PLS analysis method.

5. Results and Discussion

5.1 KF Method

Figs. 6 and 7 show the deformation signals obtained for south tower before and after processing of KF in two directions X & Y respectively.

From these figures, it was found that the amplitude of GPS signals is abnormal. This indicates that the tower is unstable under applied loads. Also the figures indicate that the maximum and minimum ranges of deformation in X & Y-directions are 3.11 cm, 2.34 cm and 0.42 cm, 0.32 cm, respectively. For these deformations it was found that the standard deviations (SD) were 8.25 mm and 6.74 mm respectively.

5.2 PLS Method

The relationships between X & Y-coordinates with monitoring time are shown in Figs. 8 and 9.

From the figures, it can be seen that after six months of bridge opening the deformation in X & Y directions are 0.087 m and 0.058 m respectively. This can be attributed to the increased in applied traffic loads at mid span.

The results also revealed that the accurate coordinates values using KF and PLS are much close (see Figs. 10 and 11). For KF and PLS methods, it was found that the maximum SD in X-direction is 0.003230184 m and 6.95E-06 m, respectively, whereas the maximum SD in Y-direction is 0.000789298 m and 1.70E-06 m, respectively.

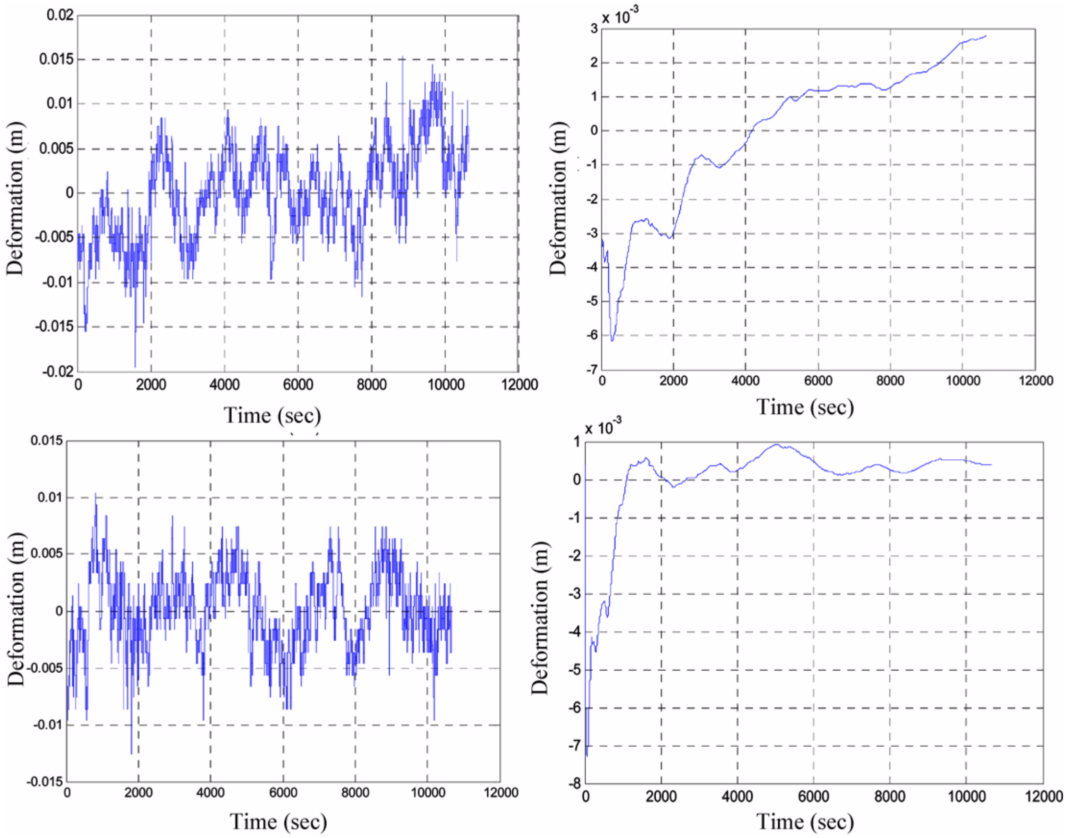


Fig. 6. The Time Series of *X* (up) and *Y* (dawn)-direction for S. Tower (before and after KF) (1-8-2007)

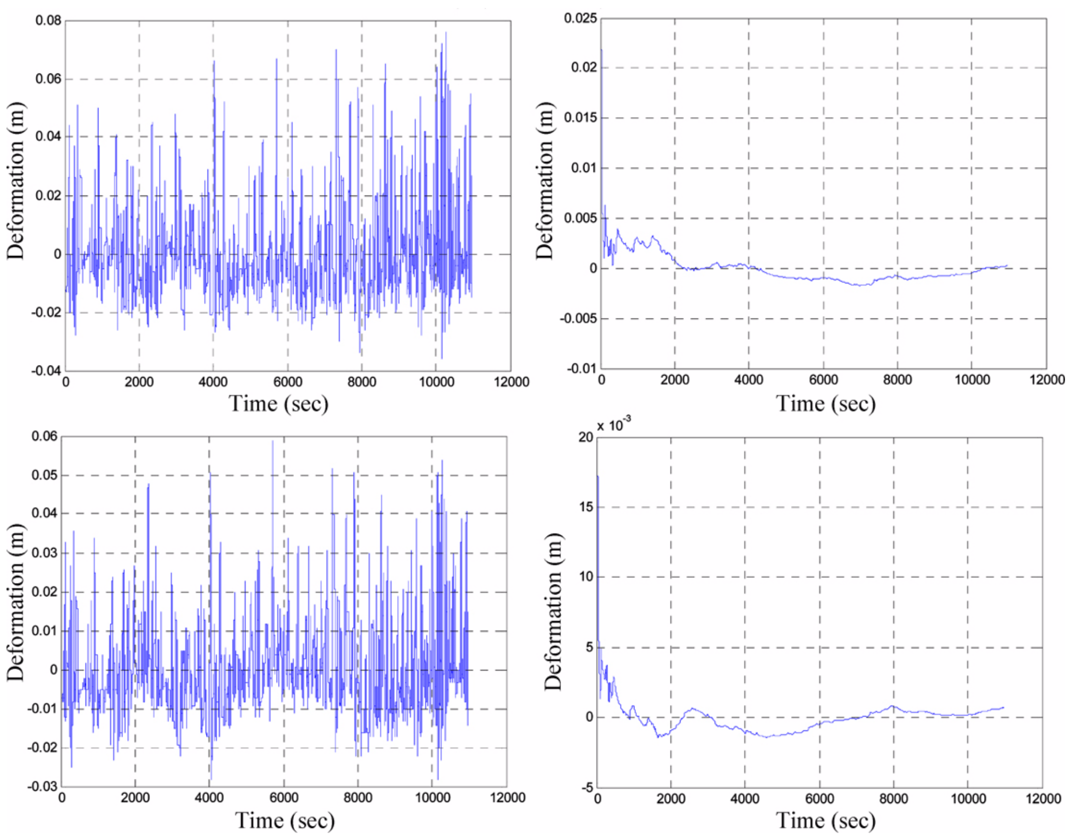


Fig. 7. The Time Series of *X* (up) and *Y* (dawn)-direction for S. Tower (before and after KF) (1-6-2008)

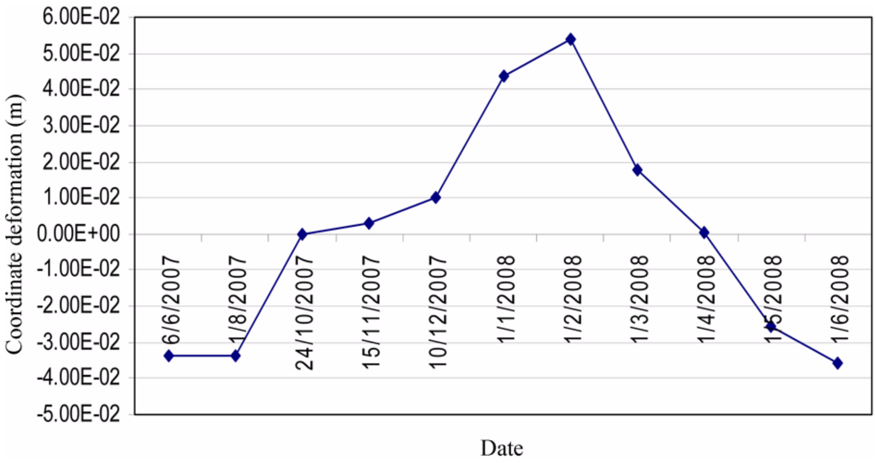


Fig. 8. Corrected *X* Coordinate of S. Tower from PLS

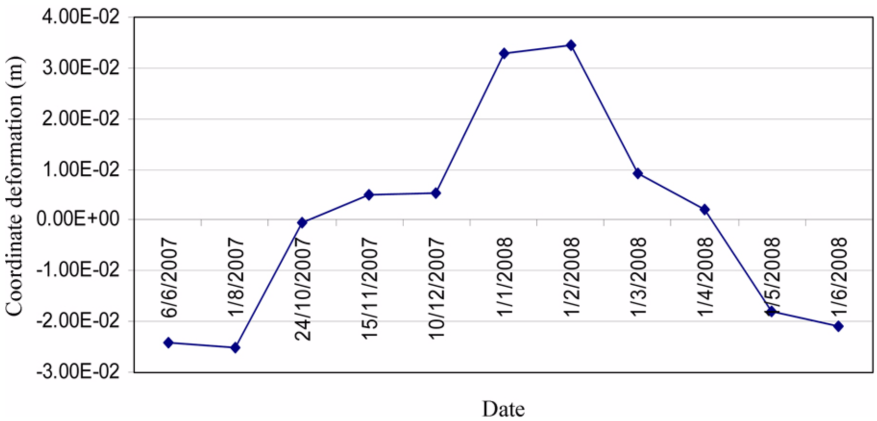


Fig. 9. Corrected *Y* Coordinate of S. Tower from PLS

6. Statistical Analysis

SPSS statistical software (SPSS, 1999) was used to determine the deformation. Deformation results were statistically analyzed with a 5% level of significance.

6.1 F-Test

Damage in the bridge tower has been determined using the similarity transformation approach sited in (Chen, 1983; Acar *et al*., 2006) as described in section 4. F-test statistical analysis has been adopted to find out the deformation in the tower. In this analysis, the deformation (d) for point i in Eq. (12) was determined respect to the p, which was assumed as reference point before with bridge loading. Herein, it should be mentioned that all of these points were located on the same datum (c).

$$d = \begin{bmatrix} d_x \\ d_y \end{bmatrix} = \begin{bmatrix} x_c^i - x_c^p \\ y_c^i - y_c^p \end{bmatrix} \tag{12}$$

$$|D| = \sqrt{d^T d} \tag{13}$$

Whereas: T_J value for the selected point in two directions is computed as follows (Zainal *et al*., 2004).

$$T_J = \frac{D_{1J}^T Q_{D1J}^{-1} D_{1J}}{2\sigma^2} \approx F(\alpha, 2, df) \tag{14}$$

$$\sigma^2 = \frac{|(\sigma_1^2)(df_1) + (\sigma_2^2)(df_2)|}{df} \tag{15}$$

Where: D_{1J}, and Q_{D1J} are the displacement vector and cofactor matrix of each datum point J. σ_1, df_1 are a posteriori variance factor and the degree of freedom in epoch 1. σ_2, df_2 are a posteriori variance factor and the degree of freedom in epoch 2. $df = df_1 + df_2$, sum of degrees of freedom of epochs 1 and 2.

Then, if $T < F$ the point isn't moved, and if $T > F$ the point is moved (Schroedel, 2002). The results are shown in Table 3.

From Table 3, it was found that the deformation values in the X-direction occurred on October 2007 to April 2008 varied between 0.033353 m and 0.034120 m, whereas, these values were found to be between 0.023527 m and 0.026366 m in Y-direction. This is related to the bridge loading that opened on August 2007. It should be mentioned herein, that due to the traffic loads the S-tower is moved towards inner side of the bridge. Accordingly, the crack width happened on abutment is larger than that located on the mid span as shown in Fig. 12. This is attributed to the weakened bond between the concrete and steel bars.

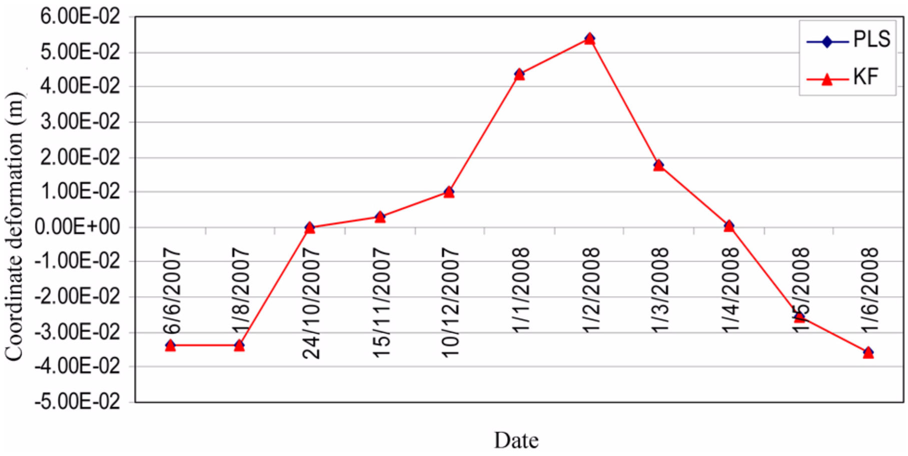


Fig. 10. Corrected *X* Coordinate of S. Tower from KF and PLS

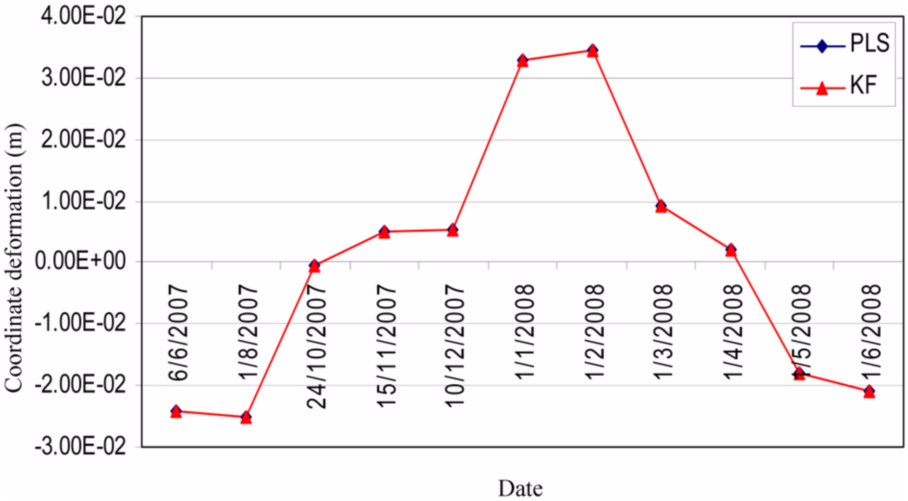


Fig. 11. Corrected *Y* Coordinate of S. Tower from KF and PLS

Table 3. The Results of Statistical Test

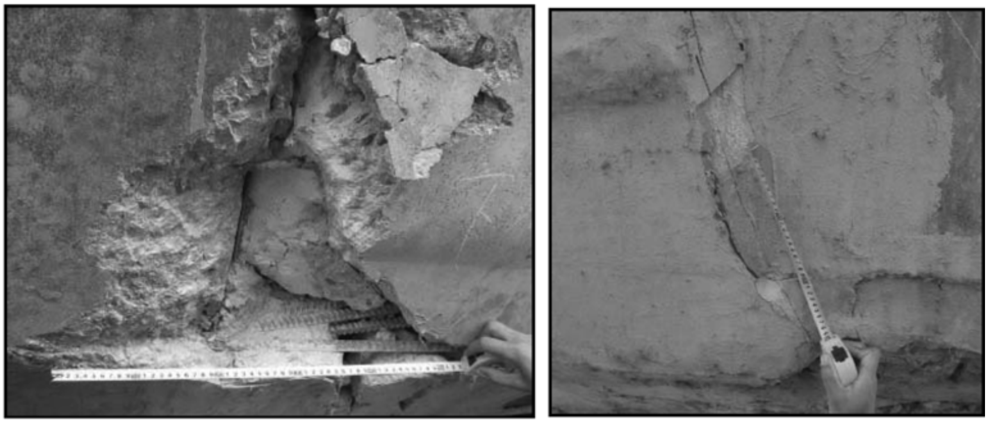
Monitoring Date	$dX=(X_i-X_1)$	F-Test	$dy=(Y_i-Y_1)$	F-Test	Note
1/8/2007	0.000245	N	0.001077	N	No. deformation
24/10/2007	0.033353	Y	0.023527	Y	deformation
15/11/2007	0.036710	Y	0.029160	Y	deformation
10/12/2007	0.043847	Y	0.029606	Y	deformation
1/1/2008	0.077324	Y	0.056974	Y	deformation
1/2/2008	0.087361	Y	0.058642	Y	deformation
1/3/2008	0.051392	Y	0.033368	Y	deformation
1/4/2008	0.034120	Y	0.026366	Y	deformation
1/5/2008	0.007859	N	0.006182	N	No. deformation
1/6/2008	0.002324	N	0.003199	N	No. deformation

Where, (X_1, Y_1) coordinates on 6 July 2007 (Datum), (X_i,Y_i) coordinates on date i.
All values in (m)

7. Conclusions

Based on this limited study, the analysis of result leads to the following findings:

1. The proposed surveying techniques using DGPS and RTK can provide valuable deformation data of the structural members.
2. It was found that the calculated coordinates from PLS and KF



(a) (b)

Fig. 12. Cracks Shape at (a) Abutment and (b) Mid Span, Respectively

analysis methods are much close.

3. The SD obtained from multiple processing analyses of GPS data was increased significantly. This indicates that more accurate deformation value can be captured.
4. It was found that the traffic loads are the main factor affecting bridge cracks.
5. After six months of bridge opening, the maximum deformation was pronounced 48.2 m far from the beginning abutment.
6. It was observed that the S-tower was returned to its original case after ten months of traffic opening.
7. The photographs demonstrate that the crack width on bridge abutment is greater than that on the mid span.

Acknowledgments

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