Assessment of Bridge Deck Movement under the Impact of Environmental Factors and Traffic Load

Trung-Hieu Ha¹,4, Tien-Yin Chou² and Yao-Min Fang¹
¹PhD program of Civil and Hydraulic Engineering, College of Construction and Development, Feng Chia University, TAIWAN.
¹Faculty of Civil Engineering, University of Transport and Communications – Campus in Ho Chi Minh City, VIETNAM
²GIS Research Center, Feng Chia University, Taichung, TAIWAN

E-mail: hatrunghieu0409@gmail.com

Abstract. The Bridge Health Monitoring (BHM) system has become crucial for long-span bridge structures. This study aims to assess the bridge deck movement based-on GPS time series data and environmental data obtained from BHM system. The correlation and regression analysis are utilized to find out the pairwise relationship between the bridge deck movement in all directions and environmental factors as well as traffic load. The result shows the highest correlations in bridge deck vertical movements, the symmetrical oscillation in different parts of bridge deck and it also reveals the impact of air temperature change, wind velocity and traffic vehicle on bridge deck movement in all directions.

1. Introduction

The purposes of BHM system are monitor the bridge structural conditions and guaranteeing the safety of bridge structures, especially for the long span bridge structures [1][2]. The operation and maintenance of bridge are becoming more and more important. In BHM system, Global Positioning System (GPS) is a crucial component because of its real-time technique and high accuracy measurement, which lead to the great opportunities for monitoring the displacement, deformation, and movement or deflection behavior of bridges under external factors such as loading vehicles or environmental impacts. GPS-based data can be effectively used for evaluating the bridge safety [3-6]. This study aims to use GPS-based time series data for evaluating the operation of bridge deck under the impact of traffic and environmental factors.

The data used in this paper are collected from BHM system in Can Tho bridge which is located in the South of Vietnam. It is the longest cable-stayed bridge in South East Asia. The BHM system has been installed in 2010, which includes many sensors such as GPS sensors, accelerometers, temperature sensors, anemometers.

4 To whom any correspondence should be addressed.
The GPS signal at each station is acquired at 20 Hz and the obtained data then be averaged to 10-minute values. The acquired data from each sensor, which includes three-direction coordinates that x, y and z reflect the longitudinal, lateral and vertical direction movements, respectively.

This paper uses GPS data in 4 sensors: 2 sensors locating at the center and 2 sensors at quarter of the bridge deck, A(\(x_A, y_A, z_A\)), C(\(x_C, y_C, z_C\)) on the upstream side and B(\(x_B, y_B, z_B\)), D(\(x_D, y_D, z_D\)) on the downstream side (Figure 1). The temperature change and wind velocity in the same interval time are also utilized. All the GPS data extracting in 3 days from January 1\(^{st}\) to January 3\(^{rd}\), 2015 are presented in Figure 2 and the statistical descriptive data are shown in Table 1.
Table 1. Data description

| Variable | Obs  | Mean   | Std. Dev. | Min    | Max    |
|----------|------|--------|-----------|--------|--------|
| x_A      | 429  | 275.2965 | 0.0035    | 275.2824 | 275.3086 |
| y_A      | 429  | -12.1290 | 0.0035    | -12.1473 | -12.1089 |
| z_A      | 429  | 42.6266  | 0.0316    | 42.5544  | 42.6774  |
| x_B      | 429  | 275.3131 | 0.0034    | 275.2975 | 275.3236 |
| y_B      | 429  | 12.2865  | 0.0056    | 12.2676  | 12.3051  |
| z_B      | 429  | 42.6279  | 0.0307    | 42.5532  | 42.6762  |
| x_C      | 429  | 412.9688 | 0.0061    | 412.9484 | 412.9865 |
| y_C      | 429  | -12.1209 | 0.0051    | -12.1355 | -12.1030 |
| z_C      | 429  | 39.9514  | 0.0199    | 39.9043  | 39.9993  |
| x_D      | 429  | 412.9550 | 0.0056    | 412.9420 | 412.9707 |
| y_D      | 429  | 12.2812  | 0.0050    | 12.2655  | 12.2990  |
| z_D      | 429  | 39.9470  | 0.0202    | 39.8871  | 39.9841  |
| temp     | 429  | 24.7033  | 1.7749    | 20.5000  | 28.2100  |
| Wind     | 429  | 3.6989   | 1.9911    | 0.0000   | 9.0852   |

2. Correlation analysis and Regression analysis in bridge deck movement assessment

To assess the bridge deck movement, the correlation coefficients between pairwise of each direction in both positions of the bridge deck are computed (i.e. x_A-x_B, x_C-x_D...). The correlation between 2 variables is defined as follow:

$$r = \frac{\sum (x - \mu_x)(y - \mu_y)}{\sqrt{\sum (x - \mu_x)^2 \sum (y - \mu_y)^2}}$$

(1)

In which $\mu_x$, $\mu_y$ are the means of x and y variables.

The results are shown in Table 2 below.

Table 2. Correlation coefficients

|       | x_A | y_A | z_A | x_B | y_B | z_B | x_C | y_C | z_C | x_D | y_D | z_D | temp | Wind |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|
| x_A   | 1   |     |     |     |     |     |     |     |     |     |     |     |      |      |
| y_A   | 0.16| 1   |     |     |     |     |     |     |     |     |     |     |      |      |
| z_A   | -0.34| 0.09| 1   |     |     |     |     |     |     |     |     |     |      |      |
| x_B   | 0.95| 0.16| -0.31| 1 |     |     |     |     |     |     |     |     |      |      |
| y_B   | 0.34| 0.84| -0.36| 0.31| 1   |     |     |     |     |     |     |     |      |      |
| z_B   | -0.33| 0.09| 0.996| -0.3| -0.35| 1   |     |     |     |     |     |     |      |      |
| x_C   | 0.61| -0.27| -0.57| 0.6 | 0.12| -0.56| 1   |     |     |     |     |     |      |      |
| y_C   | 0.23| 0.85| -0.05| 0.2 | 0.8 | -0.05| -0.18| 1   |     |     |     |     |      |      |
| z_C   | -0.25| 0.22| 0.93 | -0.24| -0.22| 0.92| -0.57| 0.09| 1   |     |     |     |      |      |
| x_D   | 0.6 | -0.16| -0.62| 0.61| 0.23| -0.61| 0.76| -0.03| -0.59| 1 |     |     |      |      |
| y_D   | 0.13| 0.76| -0.07| 0.11| 0.76| -0.08| -0.06| 0.67| 0.05| -0.07| 1 |     |      |      |
| z_D   | -0.26| 0.14| 0.94 | -0.24| -0.28| 0.94| -0.53| -0.01| 0.91| -0.6 | 0 | 1 |      |      |
| temp  | 0.22| -0.32| -0.82| 0.19| 0.11| -0.82| 0.6 | -0.16| -0.79| 0.61| -0.06| -0.78| 1 |      |
| Wind  | 0.02| 0.38| 0.05 | 0.02| 0.29| 0.05| -0.21| 0.34| 0.13| -0.19| 0.25| 0.08| -0.34| 1 |
The results show the strong correlation between the movements of bridge deck at the center points in each direction (0.95, 0.84, 0.996 in x, y, z direction, respectively), while it is seen the lower values than those at the quarter points (0.76, 0.67, 0.91 in x, y, z direction, respectively). In which, the correlation coefficient reaches to the highest values in vertical direction in both locations. This outcome refers to the symmetry in operation in different parts of bridge deck: the bridge deck tends to have symmetric oscillation at center points, whereas it is more likely to have the slight difference in movements between upstream side and downstream side. To strengthen this finding, the bridge deck torsional displacements are calculated in different time: from January 1st to January 3rd 2015, from June 1st to June 3rd 2015 and from January 1st to January 3rd 2016. The bridge deck torsion is defined as the following equation:

$$\theta = \sin^{-1}\left(\frac{z_1 - z_2}{L}\right) \times \left(\frac{\pi}{180}\right) \text{ (rad)} \tag{2}$$

Where $z_1, z_2$ are the vertical displacements at same symmetrical stations of 2 different points (point A and B, point C and D in Figure 1) and $L$ is the distance between these two stations. In this case study, $L = 24.4$(m).

The figures above indicate the range values of bridge deck torsion at quarter part are greater than those in the center part. The pairwise coefficient of variation (CV = $\frac{\sigma}{\mu} \times 100(\%)$, $\mu$ and $\sigma$ are mean and standard deviation of each data set, respectively) of bridge deck torsions at center and quarter points (AB and CD) are 70.5% and 81.3%, 80.8% and 92.3%, 82.3% and 88.9% for January 1st to January 3rd 2015, June 1st to June 3rd 2015 and January 1st to January 3rd 2016, respectively.

This has affirmed the previous findings that the movements at quarter point of bridge deck are less symmetrical than that at the center point, which refers to the higher deviations between bridge deck vibrations in both upstream and downstream sides of bridge.

Some previous studies indicate that the bridge deck movement be impacted by traffic vehicle and environmental factors such as temperature change and wind speed. The correlations between bridge deck movements in each direction are also considered. The correlation coefficients, which are also presented in Table 2, show the strongest negative relationship of temperature and vertical movement, from -0.78 to -0.82, whereas there is an insignificant correlation between wind velocity and deck movement in all directions.
Next section, the regression analysis is employed to measure the impact of wind velocity, temperature and traffic vehicle to bridge deck movement. In this case study, the bridge deck movements in all directions at 4 points are denoted as dependent variables, wind speed and temperature as independent variables and the impact of traffic vehicle here is assumed as dummy variable, in which it takes the values 1 indicating the presence of traffic vehicles on bridge from the time of 8h00 to 20h each day and the values 0 referring the absence of traffic vehicles from 0h to 7h59 and 20h01 to 23h59. The outcome of regression analysis for the impact of air temperature, wind velocity and traffic load on \( x_A \) is presented in Table 3 below, the remainders are summarized and explained in Table 4.

Table 3. Regression analysis result of \( x_A \) reg \( x_A \) temp Wind traffic

| Source       | SS             | df   | MS           | Number of obs = 429 |
|--------------|----------------|------|--------------|---------------------|
| Model        | .00042803      | 3    | .000142677   | Prob > F = 0.0000   |
| Residual     | .004949603     | 425  | .000011646   | R-squared = 0.0796  |
| Total        | .005377632     | 428  | .000012565   | Adj R-squared = 0.0731 |

Parameter Estimates

| xA | Coef. Std. Err. t P>|t| [95% Conf. Interval] |
|----|-----------------|-------|------------|---------------------|
| temp | .0002006 .0001418 1.41 0.158 -.0000782 .0004794 |
| Wind | .0001217 .000091 1.34 0.182 -.0000572 .0003006 |
| traffic | .0014628 .0004738 3.09 0.002 .0005315 .0023941 |
| _cons | 275.2904 .0034913 7.9e+04 0.000 275.2835 275.2972 |

The output above shows the statistically significant p-value (Prob > F = 0.0000), which is used in testing the null hypothesis that all of the model coefficients are equal to 0 and the R-squared = 0.0796, which indicates the proportion of variance in the dependent variable \( x_A \) can be explained by the independent variables (temperature, wind and traffic). This result refers to the 7.96% of the considered factors have the impact on \( x_A \). We also pay attention to the column P>|t| in the Parameter Estimates table, which is used to test the null hypothesis that the coefficient is 0 at the level 0.05. The coefficient for temperature is not statistically significant because the p-value is 0.158, which is greater than 0.05, the same result for the coefficient of wind since p-value is 0.182. The coefficient for traffic is statistically significant because the p-value is smaller than 0.05.
Table 4. Regression analysis result for all variables

|       | p-value | R-squared | Explain |
|-------|---------|-----------|---------|
|       | Temperature | Wind | Traffic |         |
| X_A   | 0.158   | 0.182     | 0.002   | 0.0796  | The temperature changes and wind speed do not have significant impact on X_A. |
| Y_A   | 0.000   | 0.000     | 0.000   | 0.2363  | The impact of temperature, wind speed and traffic to the movement of deck at Y_A is 23.63%. |
| Z_A   | 0.000   | 0.000     | 0.000   | 0.7722  | The impact of temperature, wind speed and traffic to the deck movement at Z_A is 77.22%. |
| X_B   | 0.278   | 0.226     | 0.004   | 0.2780  | The temperature changes and wind speed do not have impact on X_B. |
| Y_B   | 0.005   | 0.036     | 0.000   | 0.4030  | The impact of temperature, wind speed and traffic to the deck movement at Y_B is 40.33%. |
| Z_B   | 0.000   | 0.000     | 0.000   | 0.7709  | The impact of temperature and traffic to the deck movement at Z_B is 77.09%. |
| X_C   | 0.000   | 0.270     | 0.001   | 0.3728  | The impact of temperature and traffic to the deck movement at X_C is 37.28%, in which wind speed does not have an impact on X_C. |
| Y_C   | 0.000   | 0.000     | 0.000   | 0.1923  | The impact of temperature, wind speed and traffic to the deck movement at Y_C is 19.23%. |
| Z_C   | 0.000   | 0.000     | 0.000   | 0.6742  | The impact of temperature, wind speed and traffic to the deck movement at Z_C on 67.42%. |
| X_D   | 0.000   | 0.696     | 0.001   | 0.3831  | The impact of temperature and traffic to the deck movement at X_D is 27.80%, in which wind speed does not have an impact on X_D. |
| Y_D   | 0.000   | 0.001     | 0.000   | 0.1906  | The impact of temperature, wind speed and traffic to the deck movement at Y_D is 19.06%. |
| Z_D   | 0.000   | 0.000     | 0.000   | 0.6704  | The impact of temperature, wind speed and traffic to the deck movement at Z_D is 67.04%. |

The results from regression analysis have shown:

- Those 3 considered factors have the impact in both y and z direction in all points of movement observations, in which the highest influence on bridge deck vertical movement (around 67% and 77%, corresponding to center points and quarter points, respectively);
- At bridge deck center points (A,B), temperature change and wind velocity do not have the impact on x direction movement;
- At bridge deck quarter points (C,D), wind speed does not have the impact on x direction movement.

3. Conclusion

In This study employed the correlation analysis and regression analysis to evaluate the bridge deck movements based on the time series observations obtaining from bridge monitoring system. The results have indicated the findings as following points:

- There are strongest correlations between the bridge deck vertical movement among all directions at different points.
- The bridge deck has symmetrical oscillation at center points, whereas it is more likely to have the slight difference in movements between upstream side and downstream side of the deck.
– The relationship between temperature and bridge deck vertical movement is strongly correlated, whereas there is an statistically insignificant correlation between wind velocity and deck movement in all directions.
– Air temperature change, wind speed and traffic load have the impact in both lateral and vertical direction at all direction movement of the considered points in the center of bridge deck.

The data used in this study only be extracted in three days. For a stronger conclusion, more data in different interval times of monitoring could be used, which would be put into the future works of bridge safety assessment.

Reference
[1] Qipei Mei, Mustafa Gül, Marcus Boay 2019 Indirect health monitoring of bridges using Mel-frequency cepstral coefficients and principal component analysis. Mechanical Systems and Signal Processing 119 523–546
[2] Bin Chen at al 2014 Integrated System of Structural Health Monitoring and Intelligent Management for a Cable-Stayed Bridge. The Scientific World Journal. 2014, Article ID 689471
[3] Ting-Hua Yi, Hong-Nan Li, Ming Gu 2013. Experimental assessment of high-rate GPS receivers for deformation monitoring of bridge. Measurement 46 420–43
[4] Hepi Hapsari Handayani, Yuwono, Taufik M. 2015 Preliminary study of bridge deformation monitoring using GPS and CRP (case study: Suramadu Bridge). Procedia Environmental Smart Structures and Systems Sciences 24 266 – 276
[5] Mosbeh R. Kalloop 2012 Bridge safety monitoring based-GPS technique: case study Zhujiang Huangpu Bridge., 9 473-487
[6] Hyo Seon Park at al 2008 Application of GPS to Monitoring of Wind-Induced Responses of High-Rise Buildings. Struct. Design Tall Spec. Build. 17, 117–132 (2008)