Maximum deflection of three span continuous bridge using rotation data based on 3 dimensional model

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Abstract. The Structural Health Monitoring System on the bridges continue to develop to ensure that the bridge being monitored is in good condition to serve traffic. One of the main bridge’s parameter observed is deflection of the bridge. Various methods has been developed to be able to monitor deflection accurately and economically. This study presents a method of determining the maximum deflection of a three-span continuous bridge using rotation data obtained from a tilt meter with linear regression. Initial data were obtained from FEM simulations under various load conditions to obtain the maximum deflection value and the rotations. Furthermore, linear regression was carried out to obtain the relationship between the four rotational data and the maximum deflection. The accuracy of the maximum deflection value is then compared with the results of the analysis using FEM. The accuracy rate obtained in this study is about 93.6%.

Keywords: Bridges, Structural Health Monitoring Systems, Maximum Deflection, Rotation

1. Introduction

Bridges are infrastructures that experience dynamic and repetitive loads in the long term during their services, therefore they have the potential to experience deterioration from time to time. To ensure the bridge is always in good condition, it is necessary to continuously monitor the bridge condition. In the recent years, the Structural Health Monitoring Systems (SHMS) were introduced which describe a number of monitoring methods implemented in full-scale civil buildings, including bridges, with the aim of helping the owner of the structure to obtain information on performance of the structure continuously. The selected monitoring system is considered based on its function, cost, technology, monitoring method and physical condition or location of the structure. During the monitoring activities several structure parameter will be measured and analysis in order to conclude the real time condition of the structure [1] [2] [3].

Vertical deflection is the most important structural parameter to be monitored both in the short and long term or to be measured in a load test for the purpose of predicting abnormal conditions and ensuring the safety of the entire bridge. For bridges over rivers, trains, or roads, the direct measurement method is impractical. GPS technology for monitoring deflections is expensive. The
method of measuring bridge deflection by utilizing rotation data from the tiltmeter can overcome this
difficulty. This method offers a simple, practical and inexpensive way to measure static and dynamic
deflection in bridge spans for a variety of vehicle loads, even for bridge spans crossing
heights. Tiltmeter is a sensor to measure the magnitude of the bridge rotation which is now widely
studied by researchers and practitioners use [4] [5] [6] [7].

With all of the problem identified above, therefore it is very important to know the relationship
between deflection and rotation. A better understanding of the relationship between deflection and
rotation, will make it easier for practitioners to assess the condition of the bridge based on deflection.

2. Objectives

The objectives of the research is to obtain a deflection equation based on rotation data on a three-
span continuous bridge modeled with a 3-dimensional finite element model and to determine the
accuracy of the deflection-rotation equation for the case of three-dimensional (3D) bridge structures.

3. Methodology

The methodology of this research are as follow

a. The research was carried out using the actual three-span continuous bridge data located at Central
   Java, Indonesia
b. 3-dimensional Finite Element Method model of the bridge is developed for this study
c. The actual maximum deflection and Rotation data area obtained by applying various load
   condition to the 3 dimensional Finite Element Method model of the bridge.
d. Equations to calculate maximum deflection from rotation data is obtained by implementing
   Multiple Regression which using Statistics software.
e. The maximum deflection obtained using the statistic equation then verified by comparing the
   value with the maximum deflection obtained from 3D structural analysis using the FEM structure
   analysis software.

4. Case Study

The case study considered in this research is as presented in Figure 1 and Figure 2.

![Figure 1 Bridge Configuration [8]](image-url)
Three-dimensional Finite Element Model of the bridge has been develop to represent the actual condition of the bridge. The Finite Element Model of the bridge includes bridge supports, girders, diaphragms and bridge deck as presented in Figure 3.

Figure 3 3-Dimensional Finite Element Method Model of the Bridge

5. Maximum Deflection and Rotation Data

To generate the maximum deflection and rotation data, there are 28 load configuration are considered as shown in the Table 1. The Maximum Deflection Data and Rotation generated for each load configuration is presented in Table 2.
| No | Load Configuration | No | Load Configuration |
|----|--------------------|----|--------------------|
| 1  | ![Load Configuration 1](image1) | 15 | ![Load Configuration 15](image15) |
| 2  | ![Load Configuration 2](image2) | 16 | ![Load Configuration 16](image16) |
| 3  | ![Load Configuration 3](image3) | 17 | ![Load Configuration 17](image17) |
| 4  | ![Load Configuration 4](image4) | 18 | ![Load Configuration 18](image18) |
| 5  | ![Load Configuration 5](image5) | 19 | ![Load Configuration 19](image19) |
| 6  | ![Load Configuration 6](image6) | 20 | ![Load Configuration 20](image20) |
| 7  | ![Load Configuration 7](image7) | 21 | ![Load Configuration 21](image21) |
| 8  | ![Load Configuration 8](image8) | 22 | ![Load Configuration 22](image22) |
| 9  | ![Load Configuration 9](image9) | 23 | ![Load Configuration 23](image23) |
| 10 | ![Load Configuration 10](image10) | 24 | ![Load Configuration 24](image24) |
| 11 | ![Load Configuration 11](image11) | 25 | ![Load Configuration 25](image25) |
| 12 | ![Load Configuration 12](image12) | 26 | ![Load Configuration 26](image26) |
| 13 | ![Load Configuration 13](image13) | 27 | ![Load Configuration 27](image27) |
| 14 | ![Load Configuration 14](image14) | 28 | ![Load Configuration 28](image28) |
6. Regression Equation to Determine Maximum Deflection

The deflection and rotation values presented in Table 2 then processed by multiple regression analysis to obtain a deflection - rotation regression equation in the form of linear equations. The regression equations are presented in Table 3.

### Table 2. The Maximum Deflection Data and Rotation Generated for Each Load Configuration

| Load Position | $\delta_1$ | $\delta_2$ | $\delta_3$ | $\phi_A$ | $\phi_B$ | $\phi_C$ | $\phi_D$ |
|---------------|------------|------------|------------|----------|----------|----------|----------|
| PB 1          | -0.549660  | -0.229045  | -0.037512  | 0.00044  | -0.000182 | 0.00038  | -0.000029 |
| PB 2          | -0.539355  | -0.804360  | 0.082141   | 0.000338 | -0.000002 | -0.00142 | 0.000075  |
| PB 3          | -0.586732  | 0.435356   | -0.598399  | -0.000468 | -0.000128 | 0.000232 | -0.000429 |
| PB 4          | -0.465316  | -0.598050  | -0.478746  | 0.000366  | -0.000038 | 0.000052 | -0.000326 |
| PB 5          | -0.433571  | -0.866614  | 0.101255   | 0.000342  | -0.000009 | -0.00026 | -0.000109 |
| PB 6          | -0.470642  | 0.660304   | -0.459632  | 0.00037   | -0.000045 | -0.000066 | -0.000292 |
| PB 7          | -0.507713  | -0.453993  | -1.020519  | 0.000397  | -0.000081 | 0.000128 | -0.000692 |
| PB 8          | -0.616598  | 0.460185   | -0.078347  | 0.000523  | -0.000264 | 0.000074 | -0.000058 |
| PB 9          | -0.495182  | -0.573220  | 0.041306   | 0.000421  | -0.000084 | -0.000106 | 0.000045  |
| PB 10         | -0.653670  | 0.666496   | -0.639234  | 0.000551  | -0.000300 | 0.000268 | -0.000459 |
| PB 11         | -0.532254  | -0.366910  | -0.519581  | 0.000449  | -0.000120 | 0.000088 | -0.000356 |
| PB 12         | -0.500508  | -0.635474  | 0.060421   | 0.000425  | -0.000090 | -0.000224 | 0.000079  |
| PB 13         | -0.537580  | -0.429164  | -0.500466  | 0.000453  | -0.000127 | -0.000030 | -0.000322 |
| PB 14         | -0.416164  | -1.462569  | -0.380813  | 0.000351  | 0.000053  | 0.000210  | -0.000218 |
| PB 15         | -0.437177  | 0.106622   | 0.14912    | 0.000406  | -0.000181 | 0.000022  | 0.000084  |
| PB 16         | -0.537352  | 0.373898   | 0.158082   | 0.000475  | -0.000240 | 7.69E-06  | 0.000083  |
| PB 17         | -0.577547  | 0.593690   | 0.088883   | 0.000504  | -0.000275 | 0.000090  | -0.000017 |
| PB 18         | -0.392665  | 0.240397   | 0.31635    | 0.000387  | -0.000192 | -6.13E-06 | 0.000125  |
| PB 19         | 0.054478   | -0.802265  | 0.078818   | -0.000019 | 0.000099  | -0.000144 | 0.000074  |
| PB 20         | 0.239360   | -1.155828  | 0.306285   | -0.000136 | 0.000181  | -0.000240 | 0.000216  |
| PB 21         | 0.199165   | -0.935766  | 0.237086   | -0.000107 | 0.000146  | -0.000158 | 0.000116  |
| PB 22         | 0.093530   | -0.668490  | 0.246048   | -0.000038 | 0.000087  | -0.000129 | 0.000115  |
| PB 23         | 0.278412   | -1.022053  | 0.473515   | -0.000155 | 0.000170  | -0.000225 | 0.000257  |
| PB 24         | 0.170568   | -1.897925  | 0.217586   | -0.000117 | 0.000272  | -0.000443 | 0.000211  |
| PB 25         | 0.315255   | -2.031426  | 0.375854   | -0.000206 | 0.000319  | -0.000456 | 0.000253  |
| PB 26         | 0.133497   | -1.691614  | -0.343001  | -0.000090 | 0.000235  | -0.000249 | 0.000190  |
| PB 27         | 0.278184   | -1.825115  | -0.185033  | -0.000178 | 0.000283  | -0.000263 | -0.000148 |
| PB 28         | 0.357430   | -1.911402  | 0.051396   | -0.000226 | 0.000307  | -0.000329 | -6.42E-06 |

*δ (cm) ; φ (radian)

Table 3. Maximum Deflection as a function of rotations

| Span | $R^2$ | $\delta_1 = 0.0766 - 1519.5\theta_A - 447\theta_B + 147\theta_C - 14.7\theta_D$ | $\delta_2 = -0.1739 - 1491\theta_A - 5088\theta_B + 1458\theta_C + 480\theta_D$ |
|------|-------|---------------------------------------------------------------------------------|---------------------------------------------------------------------------------|
| AB   | 1.00  |                                                                                 |                                                                                 |
| BC   | 0.997 |                                                                                 |                                                                                 |
7. **Accuracy of the Maximum Deflection**

The accuracy of the approach has been investigated by comparing the maximum deflection from FEM model with the maximum deflection from the regression equation. The result of accuracy check is presented in Table 4.

| Load Position | FEM      | Regression | FEM-Reg | (FEM-Reg)/FEM (%) |
|---------------|----------|------------|---------|-------------------|
| PB 1          | -0.550   | -0.5157857 | -0.0338743 | 6.16              |
| PB 2          | -0.428   | -0.4162768 | 0.0119672 | 2.79              |
| PB 3          | -0.587   | -0.5648777 | 0.0218543 | 3.72              |
| PB 4          | -0.465   | -0.4654028 | 8.680E-05 | 0.03              |
| PB 5          | -0.434   | -0.4515056 | 0.0310332 | 7.16              |
| PB 6          | -0.471   | -0.4990781 | 0.0191364 | 4.07              |
| PB 7          | -0.508   | -0.4990781 | 0.0086349 | 1.70              |
| PB 8          | -0.617   | -0.6101159 | 0.0064821 | 1.05              |
| PB 9          | -0.495   | -0.5106410 | 0.0154590 | 3.12              |
| PB 10         | -0.654   | -0.6591932 | 0.0055232 | 0.84              |
| PB 11         | -0.532   | -0.5597183 | 0.0274643 | 5.16              |
| PB 12         | -0.501   | -0.4971908 | 0.0033172 | 0.66              |
| PB 13         | -0.538   | -0.5458211 | 0.0081411 | 1.53              |
| PB 14         | -0.416   | -0.4463609 | 0.0301969 | 7.26              |
| PB 15         | -0.423   | -0.4574108 | 0.0256938 | 5.95              |
| PB 16         | -0.537   | -0.5402336 | 0.0028816 | 0.54              |
| PB 17         | -0.578   | -0.5792831 | 0.0017361 | 0.30              |
| PB 18         | -0.393   | -0.4265583 | 0.0338933 | 8.63              |
| PB 19         | 0.0545   | 0.0812977   | 0.0268197 | 49.23             |
| PB 20         | 0.2394   | 0.2344498   | 0.0049102 | 2.05              |
| PB 21         | 0.1992   | 0.1954453   | 0.0037197 | 1.87              |
| PB 22         | 0.0935   | 0.1127245   | 0.0191945 | 20.52             |
| PB 23         | 0.2784   | 0.2654296   | 0.0129824 | 4.66              |
| PB 24         | 0.1706   | 0.1948168   | 0.0242488 | 14.22             |
| PB 25         | 0.3153   | 0.3103369   | 0.0049181 | 1.56              |
| PB 26         | 0.1335   | 0.1477060   | 0.0142090 | 10.64             |
| PB 27         | 0.2782   | 0.2614066   | 0.0167774 | 6.03              |
| PB 28         | 0.3574   | 0.3312354   | 0.0261946 | 7.33              |
| **Average**   | 0.01334648 |            | 6.39     |                   |

It can be seen in Table 4 that the average difference of FEM deflection and regression equation is 6.39%. The different in maximum deflection value is relatively small. The difference for PB 19, PB 22, PB 24 and PB 26 are relatively high, these are due to the relatively small deflection value of the cases considered.

8. **Conclusion and Recommendation**

Based on the results of the analysis of the research conducted it can be concluded that:

a. This study shows that the application of regression formula to predict the maximum deflection value at 3 span continuous bridge provide relatively good accuracy.

b. Therefore, tilt meter sensor can be utilized to measure the rotation for maximum deflection of bridge to provide economical structural monitoring system
c. The accuracy of the regression equation may further increase by using higher order of regression
d. It is suggested to conduct field test application of the system in the real bridge.

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