BWIM-based Overweight Vehicle Enforcement Technique for Intelligent Transportation Systems of Ubiquitous City

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Abstract
Although vehicle driving test for the development of BWIM system is necessary, but it needs many cost and time in addition application of various driving condition. Thus, we need the numerical-simulation method resolving the cost and time problems of vehicle driving test and the way of measuring response of bridge according to the various driving condition. Using the precision analysis model reflecting the dynamic characteristic is contributed to increase accuracy in numerical simulation. In this paper, we conduct a numerical simulation to apply precision analysis model, which reflect the dynamic characteristic of bridge using Bridge Weigh-in-Motion technique and suggest overload vehicle enforcement technology using precision analysis model.

Keywords: Bridge Weigh-In-Motion(BWIM) system, Precision analysis model, Dynamic characteristic of bridge, Numerical simulation

1. Introduction
Operation of overload vehicle on the bridge is main cause in the bridge damage and decrease of bridge lifespan. Moreover, for the cost of repair in the bridge increase 2 times the usual day [1]. In addition, approximately 480 billion won is used to repair the road/bridge and, related charge have increased every year [2]. Existing overload enforcement system has many ways of the enforcement evasion such as axial control, inducement of malfunction and use of detour, durability of equipment and operation problem cause the low enforcement record [1]. In order to solve these drawbacks, the studies for development of BWIM system, which estimates the axial load and total load while the overload vehicle pass the bridge have been conducted. Although vehicle driving test for the development of BWIM system is necessary, but it needs many cost and time in addition application of various driving condition. Thus, we need the numerical-simulation method resolving the cost and time problems of vehicle driving test and the way of measuring response of bridge according to the various driving condition. Using the precision analysis model reflecting the dynamic characteristic is contributed to increase accuracy in numerical simulation. In this paper, we conduct a numerical simulation to apply precision analysis model, which reflect the dynamic characteristic of bridge using Bridge Weigh-in-Motion technique and suggest overload vehicle enforcement technology using precision analysis model. And, in the future, it is expected that ITS(Intelligent Transport systems) and this technology will link.

2. BWIM (Bridge Weigh-in-Motion) Theoretical Background
BWIM (Bridge Weigh-in-Motion) system estimate axial load and total load using response of bridge, which have various measurement method such as static influence line method, dynamic influence line method and artificial neural network method. In this paper, we apply to the dynamic influence line method which can reflect the dynamic characteristic of bridge.

2.1 Dynamic Influence Line
The dynamic influence method is that when the vehicle passes through the bridge at any point, it measures the bridge response and present polynomial using the regression analysis. And,
the calculated response and the measured response are expressed generally as a polynomial function by the least squares method [3].

\[
E = \sum_{j=1}^{T_{\text{max}}} \left[ \varepsilon_i(j\Delta t) - \varepsilon'_i(j\Delta t) \right]^2 = \sum_{j=1}^{T_{\text{max}}} \left[ \sum_{n=1}^{N_{\text{max}}} [P_n \cdot f_i(x(t))] - \varepsilon'_i(j\Delta t) \right]^2
\]  

(1)

Where \(\varepsilon_i(j\Delta t)\) and \(\varepsilon'_i(j\Delta t)\) are the calculated response and estimated response, estimated response present \([P_n \cdot f_i(x(t))]\) again. In addition, \(t\) is time, \(n\) is the number of axes, \(j\) is the number of samples, \(\Delta t\) is time interval of data. In equation (1), \(f_i(x(t))\) is the polynomial which constitute influence line and in the position of time according to the traveling speed, it can calculate influence line. In order to have a minimum value of the sum of error \((E)\), the sum of error \((E)\) make zero using partial derivatives, and, by this process, we can calculate the polynomial coefficient of influence line \([4, 5]\).

\[
\frac{\partial E}{\partial \alpha_j} = 2 \sum_{j=0}^{T_{\text{max}}} \sum_{n=1}^{N_{\text{max}}} P_n \left( \sum_{d=0}^{D_{\text{max}}} a_n \cdot x_n(j\Delta t)^d \right) \times \left[ \sum_{n=1}^{N_{\text{max}}} P_n \cdot x_n(j\Delta t)^d \right] - 2 \sum_{j=0}^{T_{\text{max}}} P_n \cdot x_n(j\Delta t)^e
\]  

\[
F = \sum_{j=0}^{T_{\text{max}}} \sum_{n=1}^{N_{\text{max}}} P_n \cdot x_n(j\Delta t)^d \cdot P_n \cdot x_n(j\Delta t)^e
\]  

\[
M = \sum_{j=0}^{T_{\text{max}}} \sum_{n=1}^{N_{\text{max}}} P_n \cdot x_n(j\Delta t)^e \cdot P_n \cdot \varepsilon'_i(j\Delta t)^e
\]  

(2)

In this equation, partial derivatives can change matrix of \([F] \cdot [A] = [M]\), and then, by calculating \([A]\) we can estimate influence line coefficient.

2.2 Separation of Axial Load

Estimation of vehicle load use dynamic influence line in paragraph 2.1 and this process also use the least squares method.

\[
\frac{\partial E}{\partial \alpha_j} = 2 \sum_{i=1}^{I_{\text{max}}} \sum_{j=0}^{T_{\text{max}}} \sum_{n=1}^{N_{\text{max}}} A_n \cdot I_{mi}(x_n(j\Delta t)) \cdot I_{mi}(x_n(j\Delta t)) - 2 \sum_{i=1}^{I_{\text{max}}} \sum_{j=0}^{T_{\text{max}}} \varepsilon'_i(j\Delta t) \cdot I_{mi}(x_n(j\Delta t)) - 2 \sum_{j=0}^{T_{\text{max}}} P_n \cdot x_n(j\Delta t)^e \]  

\[
F = \sum_{i=1}^{I_{\text{max}}} \sum_{j=0}^{T_{\text{max}}} I_{ni}(x_n(j\Delta t)) \cdot I_{mi}(x_n(j\Delta t))
\]  

\[
M = \sum_{i=1}^{I_{\text{max}}} \sum_{j=0}^{T_{\text{max}}} \varepsilon'_i(j\Delta t) \cdot I_{mi}(x_n(j\Delta t))
\]  

(5)

For the Estimation of vehicle load, in this process, partial derivatives can also change matrix of \([F] \cdot [P] = [M]\), and then, by calculating \([P]\) and applying the dynamic influence line, we can estimate axial load and total load.

3. Verification of the BWIM-Based Overload Vehicle Enforcement Technique

3.1 Selection of the Target Bridge

<table>
<thead>
<tr>
<th>Type</th>
<th>PSC-I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Hongeun-dong98–Hongje-dong301 Seoul, Republic of Korea,</td>
</tr>
<tr>
<td>Route Name</td>
<td>Uijuro</td>
</tr>
<tr>
<td>Width</td>
<td>15m</td>
</tr>
<tr>
<td>Length</td>
<td>371m(30m+30m+30m+28m+30m+30m+28m)</td>
</tr>
<tr>
<td>Life Cycle</td>
<td>1977~2013</td>
</tr>
<tr>
<td>Span</td>
<td>7 Span</td>
</tr>
</tbody>
</table>

Figure 1. Foreground and Specification of Target Bridge
In this study, we select same object bridge to utilize previous research data [6]. The target bridge was optimized to reflect the dynamic characteristic using the ambient vibration test data and this paper use optimized precision analysis model. Figure 1 shows specification and foreground of the target bridge. The target bridge name is Hongje overpass which compose total span 7 and form is PSC-I. The bridge is located in Seodaemun-gu, Seoul and the Hongje overpass has been demolished in March 2013. The length is total 371m, width is 15m. Lane is four and girder is total 7. In case of general finite element model which didn't consider to the dynamic characteristic of bridge, estimation of total load makes an error within 5%, and it is reliable but estimation of axial load makes a considerably big error. [5]. so, to confirm the change of dynamic behavior of the target bridge, we check with the natural frequency of mode 1~3 about general finite element model and precision analysis model [7]. In addition, to confirm the degree of copy in the actual driving condition, compare nature frequency of each model with ambient natural frequency which was obtained by performing ambient vibration measurement (Table 1). Based on the ambient vibration data, general finite element model occur about 20% error and precision analysis model occur about ± 1% error. As a result, in this paper, we can confirm that the use of precision analysis model copy the response of bridge in the vehicle traffic at all times.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Nature Frequency (Hz)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>General Model</td>
<td>Precision Model</td>
</tr>
<tr>
<td>Mode 1</td>
<td>3.9543</td>
<td>5.1228</td>
</tr>
<tr>
<td>Mode 2</td>
<td>5.0251</td>
<td>5.8503</td>
</tr>
<tr>
<td>Mode 3</td>
<td>12.0002</td>
<td>9.6686</td>
</tr>
</tbody>
</table>

Table1. Comparison of the natural frequency

3.2 Numerical Simulation

3.2.1 Simulation Cases

As shown figure 4, in this paper, there are two cases about test drive and verification drive. The way of numerical simulation is that we perform the time history analysis by the structural analysis program named MIDAS civil to measure the response of bridge at the lower girder point.

![Figure 4. Simulation Cases](image)

Case #1 is performed to determine the suitability of dynamic influence line which is used for the acquisition of dynamic influence line and the estimation of vehicle load. Dynamic influence line of verification vehicle in case #2 is obtained by using dynamic influence line which is result of case #1. And dynamic influence line of the verification vehicle is obtained by performing same process such as test vehicle in case #1. In all cases, the moment response is measured at mid span 14m and response is measured at all lower girder points.
3.2.2 Vehicle Specifications

Figure 5. Vehicle Specifications

<table>
<thead>
<tr>
<th></th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th></th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>6tonf</td>
<td>8tonf</td>
<td>8tonf</td>
<td>Weight</td>
<td>3.5tonf</td>
<td>3.5tonf</td>
<td>3.5tonf</td>
</tr>
<tr>
<td>L 1</td>
<td></td>
<td></td>
<td></td>
<td>L 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Axial Length</td>
<td>1.5m</td>
<td>3.5m</td>
<td></td>
<td>Axial Length</td>
<td>1.5m</td>
<td>3.5m</td>
<td></td>
</tr>
<tr>
<td>Velocity</td>
<td>80km/hr</td>
<td>Lane#2</td>
<td></td>
<td>Velocity</td>
<td>80km/hr</td>
<td>Lane#2</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5 shows the vehicle specification used for the numerical simulation. All types of vehicle are applied to the general specification according to the standard of Korea and all vehicles using the numerical simulation are assumed that vehicles drive 80 km/hr. Axial length and driving velocity is evaluated by using the bridge response, but in this paper, that process is skipped. In case #1, test vehicle is 44tonf which is applied to the criteria of regulation in Korea and verification vehicle is use for the medium truck which is same axial length with test vehicle.

3.3 Simulation Results

The load of driving vehicle is estimated through the process of paragraph 2.1 and 2.2. Result of estimated vehicle load is estimated by using measured moment response from each girder. The driving vehicle load is separated each other and the total axial load is estimated by summing each axial load. Based on the direction of driving vehicle, the left and right side axial load is judged same. So, the axial load is estimated only one direction.

Figure 7 shows the result of load estimation when 3-axial vehicle is drive at the second lane. Each axial load is 3.5tonf, 3.5tonf and 3.5tonf, and total load is 10.5tonf. As in figure 7-(a) except for the girder 1, axial load is approximately estimated, and total load is estimated from
all the girders. Except some girder the error of estimated load is occurred within about ± 8% especially, the load of estimation at the girder 6 and girder 7 is the most accurate load.

4. Conclusion
In this paper, BWIM is verified based on the precision analysis model. BWIM technology is verified by estimating the axial load and total load according to the type of driving.

1. The modal analysis of precision analysis model is performed, and, the 1% error is occurred by comparing the ambient vibration test to the result of modal analysis.
2. Numerical simulation is performed in case of the case #1 and case #2, in case of the single drive, 8% error is occurred.

In Conclusion, if suggested technology to the overload enforcement system using the precision analysis model is applied in field and BWIM technology solves the problem of reliability for the driving condition of same lane and, it will be a very practical overload enforcement system. Furthermore, in the composition of u-City's Intelligent Transportation Systems (ITS), it is expected that decreasing the cost of maintenance according to the effective management and control. In addition, this technology can secure the drivability of the road. For progressive BWIM technology, further study of the BWIM technology is necessary to find an excellent bridge type.

Acknowledgement
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