Application of Impact Echo Test Method to Detection of Separation Void between Layers of Concrete Slab Track Foundation

Jaehak Park*, Seongbaek Park**, and Yujin Lim†

Abstract

In the case of concrete slab track, construction sites have steadily increased since the opening of the second stage of the Gyeongbu Express Railway in 2008. Even though it has many advantages in respects of maintenance and track safety, unlike the initial healthy concrete track condition, defects have been found recently. Therefore, it is necessary to develop a new detection system capable of checking the defects and of performing logical decision-making process for the trackbed condition based on NDT. In this study, an impact echo test was introduced to check the possibility of developing a new NDT system for investigating cavities underneath the concrete slab track. For this purpose, small concrete slabs were constructed in backyard and have been tested by the newly proposed NDT system with impact echo. It has been shown that the new NDT system can be adapted for condition monitoring to check cavities underneath the concrete slab track.

Keywords: Concrete trackbed, Impact echo, NDT, STFT, Simple model test

1. Introduction

Since the Gyeongbu Express Railway entered the second stage of construction in 2010, the concrete track has been steadily extended. However, repair and maintenance are performed only when deformations can be clearly observed, that is, as a follow-up to visible defects. Non-destructive methods have not been employed in examining cavities underneath concrete tracks. As such, decision-making processes pertaining to repair and maintenance have lacked consideration for trackbed conditions.

Against this backdrop, this study applied the impact echo method to review the possibility of developing a non-destructive test method, so as to rapidly evaluate the integrity of the concrete track without disrupting railway operations. A concrete slab model was fabricated for this purpose, and a simple model test was conducted to determine measurement conditions and the feasibility of the proposed method.

2. Theory

2.1 Examination of Stress Waves

When a force is applied to a strong solid like concrete, the impact generates stress waves such as primary waves (P-waves), shear waves (S-waves), and Rayleigh waves (R-waves), as shown in Fig. 1. Among these three stress waves, the impact echo method uses the P-wave, which exhibits a constant propagation velocity for all frequency components. Here, the velocity \( v \) is determined by the stiffness and mass density of the material, and the propagation velocity \( v \) of the P-wave can be expressed as the product of frequency \( f \) and wavelength \( \lambda \).

When a wave is propagated from one medium to another medium, the difference in acoustic impedance at the boundary results in reflection. When cavities form beneath the concrete slab, the significantly greater difference in acoustic impedance causes the contact surface to become a reflective surface. The upper surface of the concrete slab is an air layer, and the bottom is also an air layer due to the presence of cavities, thus establishing a free-free system.
The primary resonance of the free-free system occurs when the wavelength ($\lambda$) is two times the depth ($d$).

$$\lambda = 2 \times d \quad (1)$$

The resonant frequency ($f$) can be measured when the P-wave velocity ($V_p$) of the concrete slab is known, and this is used to calculate the depth to the cavities, as given in Eq. 2.

$$d = \frac{V_{p_{\text{max}}}}{2\times f} \quad (2)$$

Sansalone [4] attributed the 5% difference between the actual depth of the concrete slab and the value calculated using Eq. 2 to the formation of a particular mode of vibration in the concrete slab arising from multiple reflections. This mode is known as the thickness mode, and Eq. 2 can be re-expressed using the shape factor ($\beta$), as given in Eq. 3.

$$d = \frac{\beta \times V_{p_{\text{max}}}}{2 \times f} \quad (3)$$

### 2.2 Basic Principle of Impact Echo Method

The impact echo method, a non-destructive method used in evaluating structures, analyzes stress waves produced when an impact is applied to a surface. It provides information on cracks, cavities, depth, and structural quality by examining waves reflected from internal cracks or the boundary of different media and resonant frequencies.

The impact echo method offers short measurement time for cavities underneath a surface, and can be applied to various structures. A general setup involves an accelerometer, used to measure the response to impact on the upper surface of concrete, and a hammer as an impact point. The resulting frequencies are processed and analyzed using the fast Fourier transform (FFT).

### 2.3 Time-Frequency Impact Echo Method (IE-STFT) for Detection of Defects in Concrete Track

The impact echo method has been selectively used in scenarios involving deep foundation elements since impact-induced stress waves propagate without directionality into a medium. However, analysis in the time domain is not possible for a concrete slab and other thinner structures due to the short travel time of the reflected waves.

To resolve the above issue, time domain signals retrieved from high speed FFT have to be converted to frequency domain signals, and the arrival time of reflected waves is estimated by identifying the resonant frequency corresponding to the maximum amplitude. In particular, the short-time Fourier transform (STFT) multiplies the function to be transformed by a window function to obtain a filtered function for a local section, and FFT is performed to analyze signal information. The frequency components derived with STFT are only for the section to which the window function is applied. Changes in frequency components over time can be assessed by varying the time values of the window function.

Table 1 presents the configuration of the equipment used...
2.4 Simulation of Cavities Beneath the Concrete Slab

A slab model measuring 125 cm in width, 110 cm in height, and 20 cm in depth was created to simulate cavities occurring between the concrete track and soil. As shown in Fig. 3, nine styrofoam cavities having different sizes were placed on a soil roadbed. At the points marked 1, 2, and 3 in the first row, styrofoam cavities measuring 300 mm x 300 mm were placed. The height of styrofoam was 50 mm in the first column (1, 4, 7), 20 mm in the second column (2, 5, 8), and 10 mm in the third column (3, 6, 9). Styrofoam measuring 200 mm x 200 mm was placed at the points marked 4, 5, and 6. Finally, styrofoam cavities measuring 100 mm x 100 mm were placed at the points marked 7, 8 and 9 in the third row.

Fig. 4 Plan of cavity simulation in small concrete slab.

Table 1. Equipment configuration for impact echo test.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acclerometer</td>
<td>Resol.(g rms) 0.002</td>
</tr>
<tr>
<td></td>
<td>freq(Hz) 1.0 ~ 10000</td>
</tr>
<tr>
<td></td>
<td>Sens(mV/g) 10</td>
</tr>
<tr>
<td>Impact</td>
<td>Steel ball 5, 7, 10, 15g</td>
</tr>
<tr>
<td></td>
<td>Hammer -</td>
</tr>
<tr>
<td>Agilent Technology</td>
<td>Bandwidth ~1 GHz</td>
</tr>
<tr>
<td></td>
<td>DC vertical gain accuracy ±2.0% full scale</td>
</tr>
<tr>
<td></td>
<td>Accuracy ±(DC vertical gain accuracy + 0.4% full scale)</td>
</tr>
</tbody>
</table>

...in the impact echo test. The setup includes an accelerometer, a DAQ board, an oscilloscope, and a laptop for data storage and processing. Also, a small steel hammer was used to produce impact.

2.5 Test Results for Cavities Under Concrete Slab

Time domain signals measured according to the cavity locations (Case 1 ? Case 9) were analyzed as frequency domain signals and STFT time-frequency signals.

A key feature of this study is that the conditions of the concrete slab were evaluated based on the center frequency and an exponential damping ratio.

For Cases 1 to 3 in the first row, the depth was calculated as 16.5 cm, 18.1 cm, and 17.7 cm, respectively, for a center frequency of 11,330 Hz, 10,350 Hz, and 10,550 Hz, and a P-wave velocity of 3,900 m/s. This is close to actual values considering how the styrofoam pieces, which represent gaps, are depressed by the weight of concrete.

The exponential damping ratio increases from 1.654% to 2.309% to 2.391% as the gaps decrease, and this can be traced to the increasing depth of concrete through which...
the elastic waves pass. Since the first row contains the largest styrofoam pieces, measuring 300 mm × 300 mm, the resonant frequency and exponential damping ratio could be easily determined.

For Cases 4 to 6 in the second row, the depth was calculated as 14.3 cm, 18.8 cm, and 16.5 cm, respectively, for a center frequency of 13,090 Hz, 9,961 Hz, and 11,330 Hz, and a P-wave velocity of 3,900 m/s. When compared to the depth values calculated for the first row, Cases 4 and 5 are fairly consistent, while Case 6 shows a relatively larger error. This may be due to the location of Case 6 being on the far right, making it more susceptible to interference from the reflected surface waves.

Case 3, which is also on the far right, has a narrower gap than Case 6. As such, the error can be seen as being under the influence of the ratio of gap depth (D) to concrete thickness (T). Similar to the first row, the exponential damping ratio increases from 1.488% to 2.935% to 5.668% as the gaps decrease.

For Cases 7 to 9 in the third row, the depth was calculuated as 14.3 cm, 18.8 cm, and 16.5 cm, respectively, for a center frequency of 13,090 Hz, 9,961 Hz, and 11,330 Hz, and a P-wave velocity of 3,900 m/s. When compared to the depth values calculated for the first row, Cases 4 and 5 are fairly consistent, while Case 6 shows a relatively larger error. This may be due to the location of Case 6 being on the far right, making it more susceptible to interference from the reflected surface waves.

Case 3, which is also on the far right, has a narrower gap than Case 6. As such, the error can be seen as being under the influence of the ratio of gap depth (D) to concrete thickness (T). Similar to the first row, the exponential damping ratio increases from 1.488% to 2.935% to 5.668% as the gaps decrease.

For Cases 7 to 9 in the third row, the depth was calculu-
Evaluation of Impact Echo Method for Concrete Track Slab Material Separation Site Measurement

Table 2. Impact echo test results of small concrete slab.

<table>
<thead>
<tr>
<th>Case</th>
<th>Size (mm)</th>
<th>Cavity (mm)</th>
<th>Slab (mm)</th>
<th>Measurement (mm)</th>
<th>Frequency [Hz]</th>
<th>Damping Ratio [%]</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>300</td>
<td>50</td>
<td>150</td>
<td>165</td>
<td>11,330</td>
<td>1.654</td>
<td>Possible</td>
</tr>
<tr>
<td>2</td>
<td>300</td>
<td>20</td>
<td>170</td>
<td>181</td>
<td>10,350</td>
<td>2.309</td>
<td>Possible</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
<td>10</td>
<td>190</td>
<td>177</td>
<td>10,550</td>
<td>2.391</td>
<td>Possible</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>50</td>
<td>150</td>
<td>143</td>
<td>13,090</td>
<td>1.488</td>
<td>Possible</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>20</td>
<td>170</td>
<td>188</td>
<td>9,961</td>
<td>2.935</td>
<td>Possible</td>
</tr>
<tr>
<td>6</td>
<td>200</td>
<td>10</td>
<td>190</td>
<td>165</td>
<td>10,330</td>
<td>5.668</td>
<td>Possible</td>
</tr>
<tr>
<td>7</td>
<td>100</td>
<td>50</td>
<td>150</td>
<td>213</td>
<td>8,789</td>
<td>6.632</td>
<td>Impossible</td>
</tr>
<tr>
<td>8</td>
<td>100</td>
<td>20</td>
<td>170</td>
<td>213</td>
<td>8,789</td>
<td>3.627</td>
<td>Impossible</td>
</tr>
<tr>
<td>9</td>
<td>100</td>
<td>10</td>
<td>190</td>
<td>177</td>
<td>10,550</td>
<td>2.966</td>
<td>Impossible</td>
</tr>
</tbody>
</table>

lated as 21.3 cm, 21.3 cm, and 17.7 cm, respectively, for a center frequency of 8,789 Hz, 8,789 Hz, and 10,550 Hz. The damping ratio was 6.632%, 3.627%, and 2.966%, respectively. The third row had a smaller D/T value than the previous two rows, and the gaps could not be determined. In Case 6, the left and right boundaries are closer than the thickness of concrete. Similarly, in Case 9, the gaps are difficult to detect as resonance because reflected waves from side boundaries are more pronounced.

Signals for which gaps can be determined based on time-frequency signals show more pronounced resonant signal characteristics, and signals parallel to the time axis tend to be longer. However, signals for which gaps cannot be determined have a wide distribution of frequencies, with time-frequency signals being parallel with the frequency axis. When the left and right boundaries of specimens are located close to the testing location, and the distance traveled by the reflected waves is smaller than the thickness of concrete, signal characteristics were difficult to determine due to the influence of reflected waves.

The results showed that gaps were difficult to detect when the ratio of gap depth to concrete thickness (D/T) was less than 1.0. That is, gaps of 200 x 200 mm or larger can be detected for a concrete thickness of 200 mm, but not local gaps smaller than 200 mm.

3. Conclusion

This study reviewed the applicability of the impact echo method as a non-destructive method of examining defects (gaps) in a concrete track.

A simple model test was performed using a slab model, and the results showed that the resonant frequency was more pronounced when the cavities were wider.

The presence of gaps was easily determined when the ratio of gap depth to concrete thickness (D/T) was greater than 1.0, but not possible at smaller ratios. Here, the height of cavities did not affect measurements. In addition, gaps were difficult to identify when the distance to the sides was closer than the distance between cavities and the surface.

The results verified the effectiveness of defect detection based on a time-frequency analysis, as well as the usefulness of the impact echo method in detecting gaps between the HSB layer and TCL layer in a concrete track.

Based on the above, a reliable system for the evaluation of concrete tracks can be developed by optimizing the proposed method for actual concrete tracks and conducting further tests to enhance reliability.

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References


