Detecting the Depth of Concrete Deterioration Using Rayleigh Wave Dispersion Based on Time-Frequency Analysis

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Abstract
The objective of this paper is to study the feasibility of using the dispersion curve of Rayleigh wave (R-wave) to evaluate the depth of concrete deterioration. In this paper, numerical analysis was performed on a 2D axisymmetric model consisting of two layers with different material properties. The top layer with a thickness of 40 mm had weaker material properties than those of the bottom layer to simulate the surface deteriorated concrete. Mechanical impact having a contact time of 50 μs was applied at a point on the top surface of the model and the displacement responses at points having various distances away from impact were recorded and analyzed. The numerical results show that the dispersion of R-wave can be observed in the displacement waveforms. However, one can have a better observation of the R-wave dispersion phenomenon at points far away from impact. The Morlet wavelet transform was carried out on the waveforms to obtain the time-frequency spectra. Subsequently, the time-frequency spectra can be used to construct the dispersion curve of R-wave. It is found that the phase velocity of R-wave increases with increasing wavelength as the wavelength is longer than twice the thickness of the top layer. Thus, the depth of the deteriorated concrete can be identified to be the half of the wavelength that makes a continuous increase in the R-wave velocity in the dispersion curve.

Keywords: R-wave dispersion, concrete deterioration, time-frequency analysis, wavelet transform

1. Introduction
There is a great demand for development of the non-destructive techniques for evaluation of concrete deterioration. Concrete degradation may be caused by fire, freezing and thawing, chemical damage (from carbonation, chlorides, and sulfates) and overloading damage (from earthquake). Concrete deterioration exists in the form of change in material properties, surface breaking cracks and/or distributed micro-cracking in the surface layer of the material. Inspection techniques based on elastic wave propagation have been developed for condition evaluation of the material either in through thickness mode or in surface mode [1-3]. Mechanical impact on the concrete surface generates stress waves with a wide range of frequencies depending on the contact time of the impact. A shorter impact duration produces stress waves with a broader range of frequencies [1]. The use of Rayleigh wave (R-wave) is one of the most promising approaches for detection of the near-surface deterioration because most of the R-wave energy propagates near surface, approximately in the depth equal to the wavelength. The amplitude of the particle motion caused by the arrival of R-wave is dominant in the waveform recorded at a point on the surface. For a multi-layered structure, R-wave with short wavelength (high frequency) can only propagate in the top layer while R-wave with long wavelength (low frequency) can penetrate into deeper layers. Consequently, the propagation behaviour of R-waves with different wavelengths is largely affected by the mechanical properties of each layer (Young’s modulus, Poisson’s ratio and mass density). In such a case, R-waves with different wavelengths travel at different phase velocities. This is the dispersion phenomenon. The dispersion curve can be plotted by presenting the variations of the phase velocity as a function of wavelength or frequency.

Spectral analysis of surface wave (SASW) was originally developed for estimating material properties in layered structures in geotechnical engineering based on the dispersion characteristics of Rayleigh waves [4,5]. Recently, application of SASW to non-destructive evaluation of concrete was on the increase [6,7]. In the SASW method, the recorded signals
are transformed into frequency domain by performing the fast Fourier transform to obtain the phase spectra. The phase difference between two recorded signals is determined by using the phase unwrapping method. Subsequently, phase velocity is calculated according to the phase difference and then the dispersion curve is generated. However, background noise in the field test can lead to the failure of phase unwrapping and an erroneous dispersion curve. The time-frequency analysis based on wavelet transform was proposed as an alternative method of the phase unwrapping method to deal with the aforementioned problem [8,9].

In this study, the Morlet wavelet transform is carried out on the waveforms recorded at receivers to obtain the time-frequency spectra that provide energy distribution in association with time and frequency. A straightforward way based on identification of the arrival time of the maximum energy caused by R-wave with a given frequency is used to develop the dispersion curve. The feasibility of using the developed dispersion curve to estimate the thickness of the deteriorated concrete layer is investigated.

2. Numerical models and impact response

2.1 Numerical models

In the studies, impact is generated by striking the concrete surface with a small steel ball (typically 3-12 mm in diameter). The strain response in concrete by such impact is low. Thus, a linear, elastic material model is valid for concrete at low strain levels. For the range of impact durations (20-80 μs) used in the studies, the frequencies in the stress pulse generated by impact are sufficiently low so that scattering at the many interfaces between the aggregate particles and cement binder in concrete is not significant. Concrete appears homogeneous to the propagating waves. Therefore, numerical models can make use of linear, elastic, isotropic material models.

An explicit, finite-element code, ANSYS-LSDYNA, was used to perform the two-dimensional axisymmetric finite element analysis of stress wave propagation in concrete. Figure 1 shows the finite element model consisting of two layers with different material properties. The top layer with a thickness of 40 mm had weaker material properties than those of the bottom layer to simulate the surface deteriorated concrete. The material properties of normal and deteriorated concrete used in the numerical analyses are listed in Table 1. These material properties resulted in Rayleigh wave velocities in normal and deteriorated concrete of 2292 and 1897 m/s, respectively. To reduce the amount of elements used in the analyses, non-reflecting boundaries were used at the side and bottom boundaries to avoid the disturbances caused by wave reflections from these boundaries.

![Fig. 1 Axisymmetric numerical model](image)
Table 1 Material properties of concrete used in numerical studies

<table>
<thead>
<tr>
<th></th>
<th>Normal concrete</th>
<th>Deteriorated concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's modulus (Pa)</td>
<td>$E_1$</td>
<td>3.488E+10</td>
</tr>
<tr>
<td>Density (kg/m$^3$)</td>
<td>$\rho_1$</td>
<td>2300</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>$\nu_1$</td>
<td>0.2</td>
</tr>
<tr>
<td>P-wave velocity (m/s)</td>
<td>$C_{P1}$</td>
<td>4105</td>
</tr>
<tr>
<td>S-wave velocity (m/s)</td>
<td>$C_{S1}$</td>
<td>2514</td>
</tr>
<tr>
<td>R-wave velocity (m/s)</td>
<td>$C_{R1}$</td>
<td>2292</td>
</tr>
</tbody>
</table>

The impact of a sphere on the specimen surface was simulated by applying a pressure loading with a force-time history of a half-cycle sine curve over the element adjacent to the axisymmetric line. The contact time ($t_c$) of the impact used in the study was 50 $\mu$s. The displacement responses at points having various distances ($H$) away from impact were recorded and analyzed.

2.2 Impact response

As illustrated in Fig. 2, the stress waves generated by impact include a dilatational (P-) wave and a distortional (S-) wave, which propagate into the structure along hemispherical wavefronts, and a Rayleigh (R-) wave, which propagates along the surface of the structure. Among the stress waves, the P-wave propagates fastest and the R-wave propagates slowest. The S-wave propagates slightly faster than the R-wave. The vertical disturbance of a particle on the impact surface caused by the R-wave arrival is much larger than that caused by the S-wave and P-wave arrivals.

![Schematic of stress wave propagation](image1)

Fig. 2 Schematic of stress wave propagation

A series of numerical analyses were performed to examine how the existence of a deteriorated concrete layer on the top surface of a concrete structure affects the stress wave propagation behaviour. First, impact response of a solid concrete without degradation was studied by performing numerical analysis on a finite element model with uniform material properties of normal concrete as listed in Table 1. The R-wave velocity of the normal concrete was 2292 m/s. Figure 3 shows the waveforms of the vertical displacement responses recorded at points having distances of 0.2, 0.4, and 1.4 m from impact, respectively. A glance at the waveforms provided in Fig. 3 reveals very similar shapes among them. All the waveforms contain a single dominant downward displacement response caused by the arrival of the R-wave and its arrival time is proportional to the distance ($H$) from impact. The arrival times of R-wave were
identified to be 88.4, 175.0, and 612.3 μs for H values of 0.2, 0.4, and 1.4 m, respectively, as indicated in Fig. 3. In such a case, there is no dispersion. This means that stress waves of different wavelengths travel at the same velocities in a solid uniform concrete.

Second, impact response of a concrete structure containing a layer of deteriorated concrete was investigated. The deteriorated concrete layer was 40-mm thick as shown in Fig. 1 and had a R-wave velocity of 1897 m/s. Figure 4 shows the waveforms of the vertical displacement responses recorded at points having distances of 0.2, 0.4, and 1.4 m from impact, respectively. The arrival of R-wave was also identified in each waveform. However, a comparison between Fig. 3 and Fig. 4 shows that the arrival of R-wave obviously delayed. In addition, unlike Fig. 3, Fig. 4 shows the change in the waveform over distance and this implies that the stress waves propagated on dispersive media due to the existence of the deteriorated concrete layer. This means that stress waves of different wavelengths travel at different velocities in this layered concrete structure. The dispersion phenomenon can be easily observed in Fig. 4(c), which was the waveform recorded at a point far enough away from impact. In Fig. 4(c), the waveform contains many R-wave arrivals with different frequencies and the R-wave with lower frequency arrives earlier than that with higher frequency. This is because the layered structure has a weak layer (deteriorated concrete) on the top surface. The propagation of R-waves having wavelengths shorter than the weak layer thickness must be limited in this weak layer and the propagation velocity is slow. When the wavelength is large enough, R-wave velocity increases with increasing its wavelength.

![Fig. 3 Impact responses of a solid concrete structure at points having a distance of H away from impact: (a) H=0.2 m, (b) H=0.4 m, and (c) H=1.4 m](image)
Fig. 4 Impact responses of a deteriorated concrete structure at points having a distance of H away from impact: (a) H=0.2 m, (b) H=0.4 m, and (c) H=1.4 m

3. Wavelet transform and dispersion curve

In the previous section, the R-wave dispersion phenomenon can be clearly observed in the waveform recorded at points far enough away from impact as shown in Fig. 4(c) for a layered structure. In this section, the Morlet wavelet transform is used to obtain the time-frequency spectra and, then, to construct the dispersion curve of R-wave. Subsequently, an explanation of how the R-wave velocity changes with wavelength will be given. Finally, the thickness of the deteriorated concrete can be estimated by identifying the wavelength at which a continuous increase in R-wave velocity occurs.

After performing the Morlet wavelet transform on the waveforms provided in Fig. 4, one can obtain the time-frequency spectra as shown in Fig. 5. In time-frequency spectra, x- and y-axis represent the time and frequency-axis, respectively, and different colours stand for the amplitude variations of stress waves. Figure 5 shows that stress waves with high amplitude response (region in red, yellow, and green) have a wide distribution of frequencies ranging from 8000 to 25000 Hz as bounded by two dotted lines. This is attributed to the stress waves generated by impact. For impact with a contact time of 50 μs, most energy were contained in stress waves having frequencies less than 25000 Hz (1.25/τc [1]).

Unlike conventional frequency spectra, the time-frequency spectra not only give the information about the frequency distribution of stress waves but also reveal the arrival time of these waves. As an example, Figs. 5(a), (b), and (c) show that the high-amplitude stress waves arrive around 100, 200, and 700 μs, respectively. However, the exact time of wave arrival is difficult to identify in the time-frequency spectra due to a wide distribution of the red-yellow-green region associated with high amplitude response. As mentioned previously, the dispersion phenomenon can be easily observed at a point far enough away from impact as discussed in Fig. 4(c). Figure 5(c) is the corresponding time-frequency spectrum and reveals a large distortion of the red-yellow-green region compared to Figs. 5(a) and (b). The distorted
region in Fig. 5(c) forms a relatively narrow band distributed from lower left to upper right, which reflects the fact that the R-wave with lower frequency arrives earlier than that with higher frequency.

Both the displacement waveforms and their corresponding time-frequency spectra exhibit the dispersion of stress waves propagating in a medium containing two layers with different material properties. How to construct the dispersion curve is the next important issue to be solved. In this study, two time-frequency spectra (Figs. 5(b) and (c)) at two separate points with the known distance of 1 m were used to develop the R-wave dispersion curve. The procedure of constructing the R-wave dispersion curve was illustrated in Fig. 6.

Fig. 5 Time-frequency spectra obtained from Morlet wavelet transform of the waveforms provided in Fig. 4: (a) H=0.2 m, (b) H=0.4 m, and (c) H=1.4 m

The bottom plot in Fig. 6(a), which was extracted by cutting a horizontal slice of the time-frequency spectrum at a specific frequency of 15000 Hz, shows an amplitude distribution over time for the receiver placed at a point 0.4 m away from impact. The highest amplitude (maximum energy) occurred at 232.64 μs in Fig. 6(a), which was the arrival time of central R-wave with 15000 Hz. Similarly, Fig. 6(b) shows that the arrival time of central R-wave with 15000 Hz was 758.15 μs for the receiver 1.4 m away from impact. With the known distance (D) between these two receivers, the arrival time difference (Δt) was used to calculate the
velocity of the R-wave \((C_R)\) with 15000 Hz. Subsequently, the associated wavelength \((\lambda_R)\) can be obtained according to the following calculations.

\[
C_R = \frac{D}{\Delta t} = \frac{(1.4 - 0.4)m}{(758.15 - 232.64) \times 10^{-6} \text{sec}} = 1903 \text{ m/s}
\]

\[
\lambda_R = \frac{C_R}{f} = \frac{19023}{15000} = 0.127 \text{ m} = 127 \text{ mm}
\]

![Fig. 6 The arrival time of R-wave with 15000 Hz: (a) H=0.4 m and (b) H=1.4 m](image)

The same procedure can be applied to different cases of R-wave with various frequencies. Table 1 lists the calculated results of R-wave velocity and wavelength for some given frequencies. According to the calculated results as listed in Table 1, the R-wave dispersion curve was constructed as shown in Fig. 7. Figure 7 shows that there is a significant change in R-wave velocity at a specific frequency, say, 80 mm in this case, which is twice the thickness of the deteriorated concrete layer. As a result, the R-wave dispersion curve can be used to detect the thickness of the deteriorated concrete, which is half the specific wavelength making a noticeable increase in R-wave velocity in the dispersion curve. It should be noted that the dispersion curve shows that the R-wave velocity of the deteriorated concrete is about 1800 m/s somewhat slower than the designated velocity of 1897 m/s. This implies that a further study is needed to interpret more precisely the time-frequency spectra.

<table>
<thead>
<tr>
<th>(f) (Hz)</th>
<th>8500</th>
<th>10000</th>
<th>12000</th>
<th>13500</th>
<th>15000</th>
<th>16500</th>
<th>17500</th>
<th>20000</th>
<th>22500</th>
<th>25000</th>
<th>40000</th>
<th>60000</th>
</tr>
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<tbody>
<tr>
<td>(C_R) (m/s)</td>
<td>2127</td>
<td>2065</td>
<td>1990</td>
<td>1936</td>
<td>1903</td>
<td>1862</td>
<td>1853</td>
<td>1820</td>
<td>1799</td>
<td>1791</td>
<td>1796</td>
<td>1804</td>
</tr>
<tr>
<td>(\lambda) (mm)</td>
<td>250</td>
<td>207</td>
<td>166</td>
<td>143</td>
<td>127</td>
<td>113</td>
<td>106</td>
<td>91</td>
<td>80</td>
<td>72</td>
<td>45</td>
<td>30</td>
</tr>
</tbody>
</table>

![Fig. 7 R-wave dispersion curve](image)
4. Conclusions

In this paper, numerical analysis was carried on a 2D axisymmetric model containing a deteriorated concrete layer on the top to observe the dispersive behaviour of impact-generated stress waves. The numerical results show that the dispersion of R-wave can be observed clearly in the displacement waveforms recorded at points far away from impact. The corresponding time-frequency spectra provide energy distribution in association with time and frequency. A straightforward way based on identification of the arrival time of the maximum energy caused by R-wave with a given frequency is used to develop the dispersion curve. It is found that the phase velocity of R-wave obviously increases when the wavelength of R-wave is twice the thickness of the top layer. Thus, it is feasible to use the dispersion curve developed by the straightforward way to estimate the thickness of the deteriorated concrete layer.

References