# Sizing Deep Surface Cracks in Concrete by Using Attenuation of Rayleigh Waves

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## 1. Introduction

In this paper, the feasibility of using Rayleigh waves (R-waves) attenuation characteristic for sizing deep surface cracks in concrete is investigated. Experiments were carried out on large concrete block specimens containing vertical slits of varying depths. To facilitate comparison, the slits were also evaluated by the P-wave time-of-flight method. In the data analysis of R-waves, relations between amplitude decay and slit depth were studied.

## 2. Specimens and Test Instrumentations

Two concrete blocks of 1 x 1 x 1 m were prepared for testing. The concrete mixture was prepared using ordinary Portland cement, maximum aggregate size of 20 mm and 4.5% entrained air. The specimens were cured under air-dried condition. The concrete achieved an average compressive strength of 29.1 MPa and a Young's modulus of 26.4 GPa at 28-day of age. Artificial cracks in the form of vertical slits of 300 mm long, 0.4 mm wide and of varying depths, *d*, were introduced into the specimens. Fig. 1 shows the plane views of both specimens. The slits were formed by removing thin metal plates of different lengths (depths), which were installed into the formwork prior to casting, at the third day after the casting. A two-sensor array was configured for the testing. Fig. 2 illustrates the sensor arrangement. Two accelerometers with a flat response up to 30 kHz were attached to the top surface of the specimens, at 150 mm away from the specimen edge and 100 mm away from the slit, resulting in allocating a 200 mm-spacing between the two sensors. Excitations of stress waves were carried out by mechanical impacts with steel ball hammers of different ball diameters ranging from 5 to 35 mm (see Fig. 3). Impacts were made at a distance of 50 mm from the sensor acting as the source channel. The sensor mounted on the other side of slit would act as the receiver. Five impacts were made on each side of slit by each hammer to produce multiple waveforms. The waveforms were then stacked to enhance signal consistency as well as increasing sound-to-noise ratio. The source-receiver sensors were then inverted and impact was repeated on the opposite side. Measurements on the sound portion of Specimen A were also carried out with similar sensor setup.

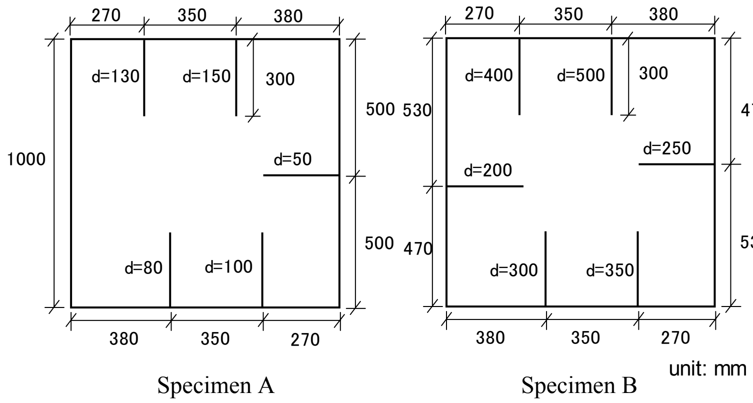


Fig. 1: Plane views of concrete block specimens

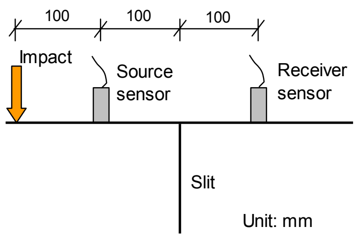


Fig. 2: Sensor arrangement

Fig. 3: Hammers for impact

## 3. Results and Discussion

<u>(i) Waveforms:</u> Fig. 4 gives example waveforms recorded from the source and receivers for different slit depths. The velocities of P-waves and R-waves were determined from the experiments as 4,050 m/s and 2,247 m/s, respectively, considering the average of several measurements taken on the sound concrete surface. The waveforms of the receivers have lower amplitude compared to that of the source because of wavefront geometric spreading and scattering at slits. It can be agreed that the deeper the slit, the greater the amplitude decay.

Keywords: amplitude factor, attenuation, concrete, non-destructive testing, Rayleigh waves, surface cracks
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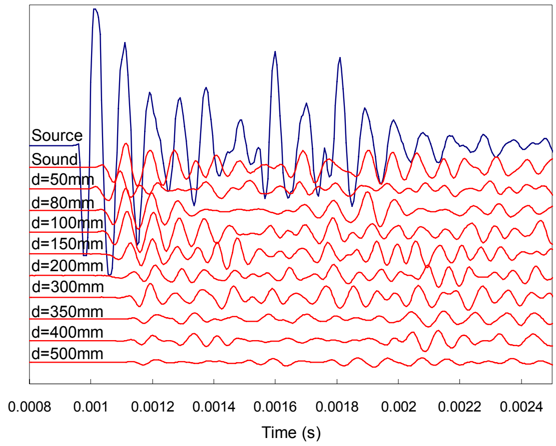


Fig. 4: Typical waveforms

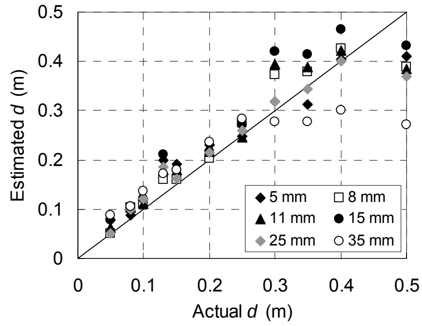


Fig. 5: P-wave TOF results by all hammers

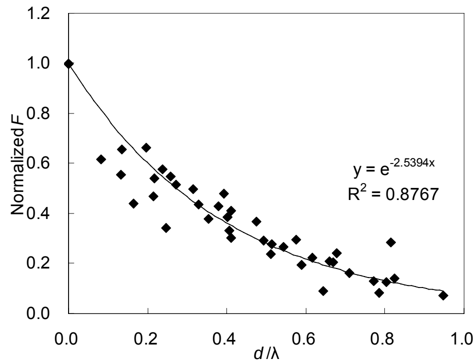


Fig. 6: Average $F$ vs. $h/\lambda$

<u>(ii) P-wave time-of-flight (TOF):</u> P-wave TOF method estimates the depth of a surface-opening cracks by considering the time needed for P-waves to travel from an impact source to a receiving point. The waves detected on the forward side of a crack are usually those diffracted from the crack tip. The results of estimation by all diameters of hammers are compared to the actual depths, given in Fig. 5. There are relatively slight discrepancies between the estimated and actual values for shallower slits. As the slit depth increases, however, the accuracy seems to decrease, especially for slits exceeding depths of 300 mm, which was their "length" in the horizontal direction. Also the results for deeper slits were less reliable as hammer diameter increases. In fact, when the depth of a slit is considerably larger than the distance between sensor and slit tip on the surface, the first arrival of wave recorded by the receiver could be that having traveled on the concrete surface. Furthermore, diffractions and scattering along the slit end in the vertical plane might have produced waves that propagated in shorter, inclined paths only to be detected by the sensor as first arrivals thereafter. Larger hammer tended to produce waves of greater energy and made easier their identification on the surface. Hence, in field assessment using the P-wave TOF method, it is essential to consider carefully probable P-wave propagation behavior with regards to the crack dimensions to assume possible limitations that affect the reliability of estimation.

<u>(iii) Amplitude decay of R-waves:</u> The feasibility of R-waves in sizing surface cracks was carried out by examining the attenuation of R-waves due to existence of a slit. The ratio between R-wave amplitudes of the source and the receiver are studied in the time domain to evaluate the decay in amplitude. The amplitudes of R-waves were determined from the peak detected after the first P-wave arrival, in both positive and negative phases. To minimize discrepancies due to sensor fixing and coupling problems, data obtained from both sides of slit was averaged. The average amplitude factors, $F$, were acquired from data obtained for each slit depth as well as from the sound portion. The factors were then normalized with that of the sound portion, respectively, to eliminate the effect of attenuation due to geometric spreading. To examine the relation between amplitude factor and slit depth, the slit depth was divided by dominant wavelength, $\lambda$, which was determined by the R-wave velocity and central frequency. The effective penetration depth of R-waves is known to be approximately one wavelength. With this, R-waves with larger wavelengths than the slit depth can be assumed to propagate in a "straightforward" path below the slit. On the contrary, for R-waves with shorter wavelengths than slit depth, propagation in less direct and more complicated paths might take place, i.e., along the slit surface and downwards before being scattered at slit end. Therefore, to avoid uncertainties in data interpretation, data that have $d/\lambda$ greater than 1.0 were removed from consideration. Fig. 6 presents the processed results by averaging of positive and negative phase amplitudes. It is noted that the data for all hammer diameters are collectively plotted as shown in the figure. The relations between average $F$ and $d/\lambda$ give a satisfactory regression to confirm the potential of the proposed methodology.

**4. Conclusions**

Satisfactory regressions were obtained for relations between the normalized amplitude factor and slit depth-to-wavelength ratio. The feasibility of using R-wave attenuation characteristic as an alternative parameter for detailed sizing of deep surface cracks in concrete structures can be confirmed. The adoption of this R-wave method can be useful particularly in cases where the P-wave-time of flight method is deemed less reliable because of various limitations by crack dimensions or measurement conditions.

References: For example, Jian et. al., "Pulsed Rayleigh Wave Scattered at a Surface Crack," *Ultrasonics*, V. 44, 2006, pp. 1131-1134.