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Effect of Concrete Surface Crack Filling Conditions on Dominant Frequency of Surface Rayleigh Wave

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Abstract. Elastic Surface Rayleigh Wave (R-wave) based non-destructive test (NDT) techniques have been studied broadly for concrete surface crack assessment in the past few decades. However, the effect of environment factors on the accuracy of R-wave NDT results are often being neglected. Sand and dust are ones of them that easily accumulate within the surface cracks of concrete structures, which potentially affect the characteristics of R-waves propagation when it travels through the concrete medium that containing cracks. This study is aimed to investigate the effect of concrete surface crack filling conditions to the dominant frequency of R-wave. Numerical simulations were conducted to study the changes of R-wave waveform when it propagated through a cracked concrete model with two various filling conditions, namely fine sand and charcoal powder. Fast Fourier Transform (FFT) for post-signal-processing (PSP) of raw R-wave signals to determine its dominant frequency. The results of numerical simulations were then justified by experimental measurements. It was found that the dominant frequency of R-wave is independent to the volume and the type of filling materials, but sensitive to the surface discontinuity of the concrete.

1. Introduction

Concrete surface crack is a common defect that can be found on civil concrete structures such as dam, bridge and most of the commercial and residential buildings. This defect is one of the indications of the degradation of concrete structures [1]. With the presence of the crack, the durability of the concrete structures may be reduced dramatically by allowing the penetration of water and other aggressive agents [2]. Therefore, concrete surface cracks detection and evaluation became a crucial step for maintaining the safety of concrete structures as early inspection allows preventive measures to be conducted to prevent damage and possible failure of the concrete structures [3]. In order to assess the concrete surface crack without further damaging the existing concrete structures, non-destructive test (NDT) is developed to fulfil this particular task.

Elastic wave is one of the popular NDT methods that have been utilised for concrete defects assessment. Recently, elastic surface Rayleigh wave (R-wave) based NDT method is broadly studied for evaluating concrete surface crack [4-8]. However, past researches which utilising R-wave in characterising concrete surface discontinuities characterisation are seldom contemplate the environmental factors that could possibly affect R-wave propagation behaviour. In an actual situation, surface cracks on concrete structures are having a certain possibility to be exposed to the natural environment that is dusty and contains moisture. Sand and dust will start to accumulate inside the surface crack after some period of time. At this moment, the applicability of NDT in the crack assessment will be doubted. The doubts can be eliminated by clearing the accumulated substances within the crack but the process is troublesome as the accessibility is low within the crack.

Saltation of sand bring fine sand particles into the surface cracks concrete structures. Besides, soot that containing mainly black carbon, which emitted from motor vehicles or originated from incomplete combustion of fuel, will eventually accumulate within the concrete surface cracks as well. For this reason, fine sand and fine charcoal powder are used in this study as the filling materials within the concrete surface crack. It is aimed to determine the effect of the proposed filling materials to the dominant frequency of R-wave.

2. Numerical Simulation

A multi-channel R-wave assessment method was adopted in this study. A commercially available software, Wave 2000 by CyberLogic Incorporation was used to simulate motions of elastic software for a series of designed numerical simulation cases. The software solves the two dimensional (2D) acoustic (elastic) wave equation based on a method of finite difference and simulating received waveforms under a variety of spatial and temporal acoustic interrogations, give as equation 1 [9]:

$$\rho \frac{\partial^2 w}{\partial^2 t} = \left[\mu + \eta \frac{\partial}{\partial t}\right] \nabla^2 w + \left[\lambda + \mu + \emptyset \frac{\partial}{\partial t} + \frac{\eta}{3}\frac{\partial}{\partial t}\right] \nabla(\nabla . w) \quad (1)$$

where ρ is material density, λ is the first Lame constant, μ is the second Lame constant, η is shear viscosity, $\emptyset$ is bulk viscosity, ∇ is the gradient of operator, $\nabla.$ is the divergence operator, ∂ is the partial differential operator, t is the time and w is a two dimensional column vector.

2.1. Parameters of Numerical Simulations

Table 1 shows the materials properties for simulation work while, table 2 presents the parameters of interest which includes the type of filling materials, volume of crack to be filled and the frequency of source excitation.

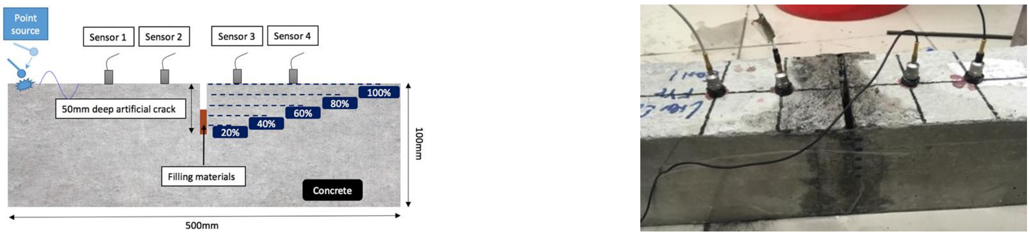
Table 1. Material properties in numerical simulations.

Parameter	Concrete	Sand	Charcoal
First Lame constant, λ [MPa]	11100	0.482	1.381
Second Lame constant, μ [MPa]	16600	0.482	0.615
Density, ρ [$\mathrm{kg/m^3}$]	2375	1212	344

Table 2. Properties of simulated crack.

Type of filling materials	Volume of crack to be filled [%]	Frequency of source excitation, f [kHz]
Charcoal powder	20, 40, 60, 80 and 100	20, 40, 60, 80 and 100
Fine Sand	20, 40, 60, 80 and 100	20, 40, 60, 80 and 100

Figure 1 (a) depicts the filled cracked simulation model with a dimension of 500 mm (width) x 100 mm (depth) in size. The material and geometry of the concrete medium were set to constant throughout the simulation works. Four sensors linear array was deployed in this study, where two of the sensors were located before and after the crack.



(a) (b)

Figure 1. (a) Schematic Diagram of Concrete Simulation Model with a Vertical Surface Crack with Filling Material (Side View) and (b) the actual set up.

3. Experimental Measurement

The concrete specimen in this study was cast with a water-to-cement ratio of 0.51, elastic modulus of 25 GPa, density of 2375 kg/m^3 and aggregate with a maximum size of 20 mm. The artificial surface crack was created by installing a 5 mm thick polystyrene board at the middle of the concrete specimen vertically, with a depth of 50 mm.

3.1. Set up of laboratory experiment.

This study adopts a four-sensor array measurement as shown in figure 1 (b), which also known as linear measurement array. Impaction of steel balls was implemented by the same operator in order to maintain the consistencies in the generation of stress waves. Different size of steel ball impactors allows generation of R-waves with varying dominant frequencies. The sizes of the steel balls used in this study were 1.0 cm, 1.5 cm, 2.0 cm and 2.5 cm. It is attempted to investigate the changes of dominant frequencies of R-wave when propagated through the surface crack filled with different materials and different volume.

4. Results

The arrival of the Rayleigh wave component can be identified after the P-wave component (the first disturbance), followed by strong bursts in the positive phases [10, 11]. By obeying this principle, R-waves were extracted from each set of raw recorded waveforms. The extracted R-wave waveforms were then processed through a series of Fourier transform using equation 2 to determine its frequency components (MATLAB®):

$$F_{k+1} = \sum_{j=0}^{n-1} \omega^{jk} A_{j+1} \tag{2}$$

Where $\omega = e^{-2\pi i/n}$ is one of the n complex roots of unity and i is the imaginary unit. A is the amplitude of recorded signals, whereas F is the computed Fast Fourier transform (FFT) of the signals. The indices j and k ranged from 0 to n-1.

4.1. Simulation results

Figure 2 displays the simulated dominant frequencies of all four receivers for the cases of sound concrete (plain concrete without absence of defect or crack), control sample (plain concrete with presence of crack), fully sand filled control sample and fully charcoal powder filled control sample with the excitation frequencies are from 20 kHz to 100 kHz, at 20 kHz increment. Several phenomena can be observed from results of laboratory experiments. {1} Dominant frequencies retrieved from each receivers in simulation cases of sound concrete remain almost constant, due to the absence of inhomogeneity and discontinuity in the concrete model that could possibly alter the propagation behaviour of R-wave; {2} Dominant frequencies recorded by Receiver 3 of each cases show a significance difference (as much as 50%) when compared to Receiver 1, 2 and 4. This indicates that R-wave dominant frequency is sensitive to the presence of flaws within a concrete, which also proved that R-wave is feasible for concrete surface crack evaluation; {3} The value of dominant frequencies of Receiver 3 is shifted to a higher value when compared to ones collected from sound concrete cases with excitation frequencies from 20 kHz to 60 kHz, but vice-versa for simulation cases with 80 kHz and 100 kHz; {4} The presence of accumulated filling materials within the concrete surface crack is not affecting the R-wave propagation behaviour. As can be seen from the insignificant changes between the dominant frequencies obtained from all the cases (less than 0.3%). Sand and charcoal powder may not possess the shear properties that required to create a bridging effect for R-wave to travel through the concrete surface crack, as R-wave propagation is strongly depends on the shear properties of the medium [12]. In addition, results analysed from 20% to 80% sand filled and charcoal filled cases are not plotted as the results are similar to the 100% filled cases, which exhibit an insensitivity towards the propagation behaviour of R-wave.

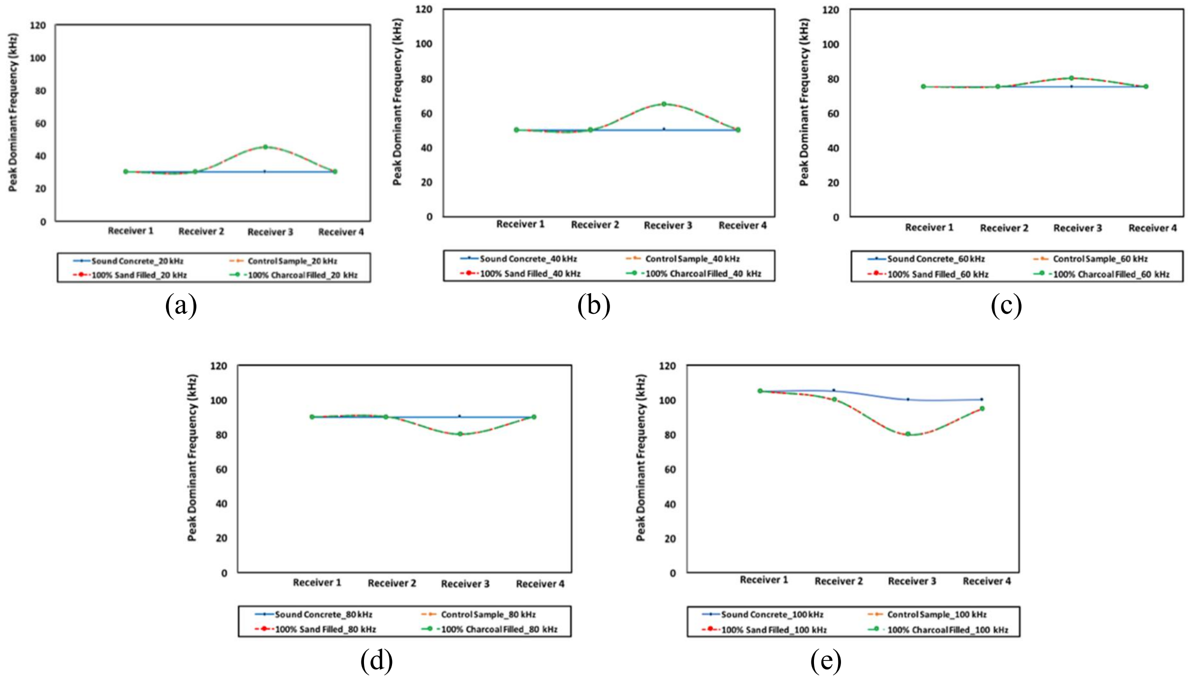


Figure 2. Collected dominant frequencies from each respective receiver for simulation cases of sound concrete, control sample and control sample fully filled by sand and charcoal powder, with the excitation frequencies of (a) 20 kHz, (b) 40 kHz, (c) 60 kHz, (d) 80 kHz and (e) 100 kHz.

4.2. Experimental verification

The experimental results justified the findings obtained from the simulation that the R-wave dominant frequency is one of the parameters that sensitive to concrete surface crack. However, it's the filling conditions do not affect the behaviour of R-waves propagation. An average of variation of 4.1% is reported when compared both of the filled and control sample cases. However, instead of Receiver 3 alone being affected as mentioned in simulation results, the dominant frequencies retrieved from Receiver 2 and 3 are both influenced by the presence of the concrete surface crack. This is due to the raw waveform collected from laboratory experiments are mixed with the reflective wave from the surface of the vertical crack. The effort to task for filtering out the reflective wave is quite challenging when compare with the waveforms recorded from numerical simulations. Further investigation should focus on this signal processing process to enhance the efficiency of the work.

5. Conclusion

It can be concluded that dominant frequency of R-wave is independent regardless the volume and the type of filling materials, sensitive to the surface discontinuity of the concrete. A maximum of 0.3% and average of 4.1% difference are reported between both filled materials and control sample cases in numerical simulations and laboratory experiments. For this reason, R-wave based NDT is practical to be utilised in concrete surface crack assessment without the needs of considering the effects of filling conditions within the crack.

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