USE OF RAYLEIGH WAVE METHODS TO DETECT NEAR SURFACE CONCRETE DAMAGE

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Abstract: Massive concrete structures, like dams, are often subjected to aggressive attacks. Weathering actions, temperature variation, chemical attacks, abrasion and other degradation processes, can act simultaneously on the concrete surface and minimise its durability. The maintenance and rehabilitation of the near surface damaged concrete zone, require a good evaluation of its degradation depth. The use of Rayleigh waves in non invasive methods, appear to be a promising approach for the determination of concrete stiffness profile. Rayleigh waves propagate in cylindrical wave fronts, parallel to the concrete surface, with elliptical particle motion. Their amplitudes decrease exponentially with depth, and most of the energy propagates in a thickness equal to the wavelength. In this paper, applications of recent multistation Rayleigh wave methods were presented. Experiments have been conducted on large volume concrete blocks (8 m3). Different typical near surface defects common to the downstream wall of concrete dams were induced in these blocks. Voids, heterogeneous layering, deterioration simulating freeze-thaw damage and horizontal fissuring, have been very well detected. Results show that this new technology can be applied on existing full scale concrete structures.

Introduction: The deterioration of the near surface concrete in dams and civil engineering structures is being an important problem. According to the national guide to sustainable municipal infrastructure 2003, canadian municipalities spend $12 to $15 billion annually on infrastructure and it never seems to be enough (National Guide to Sustainable Municipal Infrastructure 2003). Hydro-Quebec lay out more than 79 power hydraulic stations and 118 concrete massive structures, which more than half exceeded their 50 years estimated service life (Zaikoff 1991). The maintenance and rehabilitation of the near surface damaged concrete zone, require a good evaluation of the degradation depth and the existing defects. The use of Rayleigh wave non destructive testing, appear to be the most promising approach for the determination of concrete stiffness profile and the characterization of the near-surface deterioration from the surface of the concrete structures.

The basis of Rayleigh wave methods is the dispersive properties of this type of wave by which the phase velocity is a frequency dependent. Advantages of Rayleigh waves are that high percentage of the energy generated by a surface source is radiated in the form of Rayleigh waves, and the geometrical attenuation of this wave type is low because the cylindrical shape of wavefront, rather than the higher geometrical attenuation caused by the spherical wavefronts of body waves (Stokoe and Santamarina 2000). Mechanical impact on the surface of layered system, generates Rayleigh waves with various wavelengths depending on the contact time of the impact. Rayleigh waves propagate parallel to the concrete surface, with elliptical particle motion. Their amplitudes decrease exponentially with depth, and most of the energy propagates in a thickness equal to the wavelength. At a depth of 1.5 wavelength, amplitude is about 10 % its value at the surface (Sansalone and Carino 1991). The shorter is the impact duration, the broader the range of waves frequencies (Sansalone and Carino 1991). Rayleigh waves with high frequencies (small wavelengths), propagate in top layers of material while lower frequencies (long wavelengths) penetrate more deeply into the material. Affected by the mechanical properties of each layer (Young modulus, Poisson's ratio, mass density), waves with different wavelength travel at different phase velocities. The variations of the phase velocity as a function of frequency or wavelength are presented in the dispersion curve to determine the variation of the stiffness profile with depth.

Based on the 1960s applications of surface waves in measuring the elastic properties and road thickness (Jones 1958, 1962), a new two stations technique called Spectral analysis of surface waves (SASW) was developed at the University of Texas at Austin in 1980 (Stokoe et al 1994). SASW is a non-destructive testing method used to determine stiffness profiles and thicknesses of layered solid materials such as soils and pavements. SASW method is based on the spectral analysis of registered signals on the two receivers aligned with the point source on the surface of the material to be characterized. Procedure consist to convert acquired signals from the time domain to the frequency domain, using a fast fourier transform then the cross power spectrum can be calculated as a function of frequency. Finally, the phase velocity is evaluated for each frequency component from the unwrapped cross power spectrum. Applications on concrete are recent and its potential has been demonstrated in recent studies

(Kalinski 1994, Cho 2002, Rhazi et al 2002). However, this method assume the domination of the Rayleigh wave fundamental mode and ignore the importance of higher modes.

Several studies demonstrated that higher modes can contribute significantly in the dispersion curve evaluation and thus affect the accuracy of the method (Tokimatsu et al 1992, Karray and Lefebvre 2000). In order to overcome this problem, and to calculate more robust dispersion curve new multichannel Rayleigh wave methods are developed (Zywicki 1999, Park et al 1999). These multistation methods based on different signal processing procedures, showed its ability to identify and separate fundamental, higher modes and different seismic events (reflections, flexural modes).

In this paper, applications of recent multistation Rayleigh wave methods were presented. Experiments have been conducted on large volume concrete blocks (8 m3). Different typical near surface pathologies common to the downstream wall of concrete dams were induced in these blocks. In order to reduce the contribution of higher Rayleigh wave modes in the classical SASW method, a new multichannel configuration setup with filtering window and averaging approach is used to test concrete homogeneity and detect poor surface concrete quality, voids, and horizontally cracking planes. Accuracy of a new reliable signal processing technique based on frequency-wavenumber analysis of the wavefield data was demonstrated on a stratified three layers concrete volume. Results show that this new technology can be applied on existing full scale concrete structures.

Experimental program: Four high concrete volumes 3.5m×3.0m×0.8m called respectively V_1, V_2, V_3 and V_4 were made for this study, Figure 1. Typical pathologies of near surface concrete dams were simulated on these volumes in order to test the accuracy of Rayleigh wave methods to detect various defect types. Table 1 summarizes the different characteristics and the test aims of the concrete volumes. Thicknesses of concrete layers in the stratified volumes V_2 and V_3 were variable in the length direction and mechanical properties increased gradually from the top surface layer to the bottom layer as illustrated in Figures 2 and 3 . Multichannel array measurements were realized on four straight lines (L_1, L_2, L_3 and L_4) on the surfaces of concrete volumes as illustrated in Figures 1, 2 and 3. Measurement tests and their configurations are resumed in Table 2.

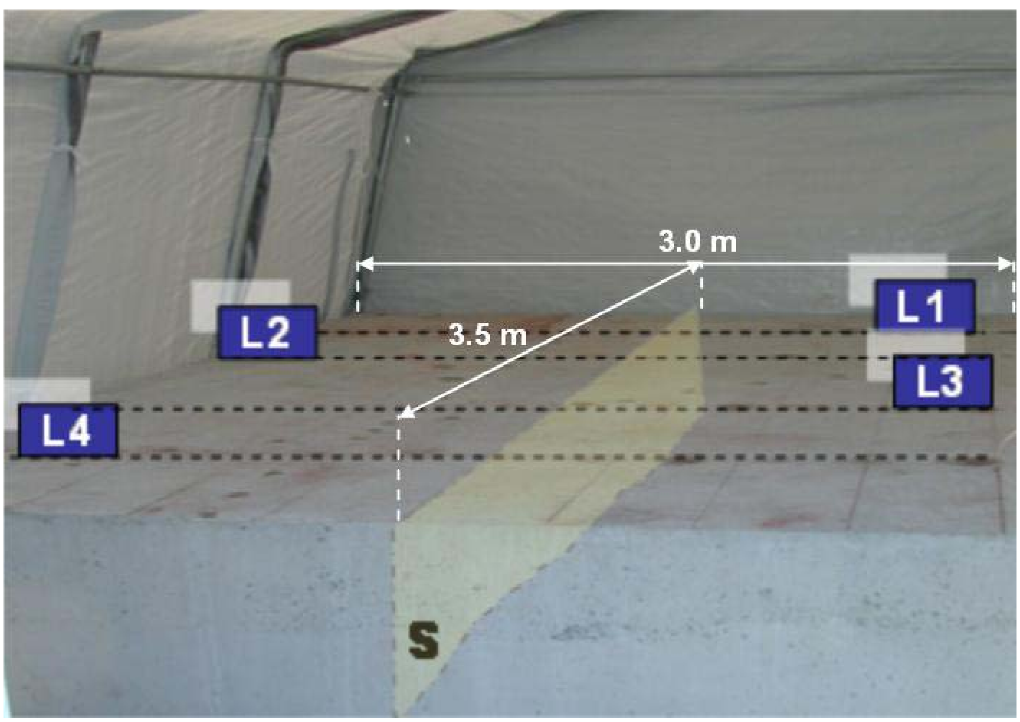


Figure 1. Example of concrete volume specimens

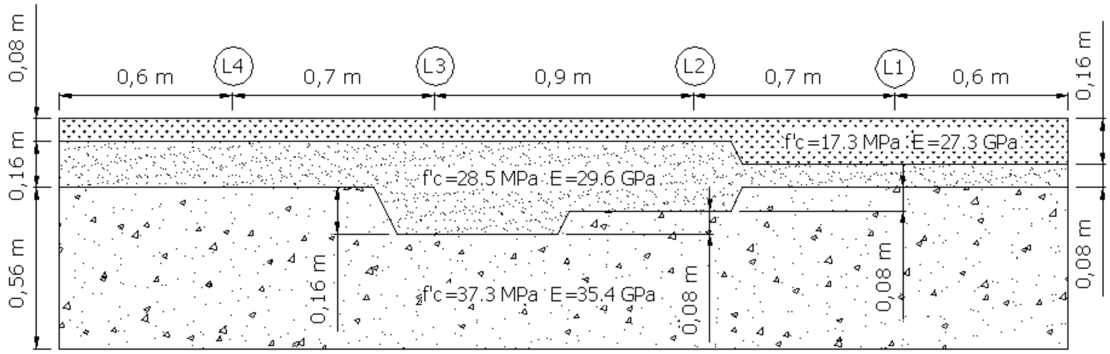


Figure 2. Longitudinal section (S) in concrete volume V_2

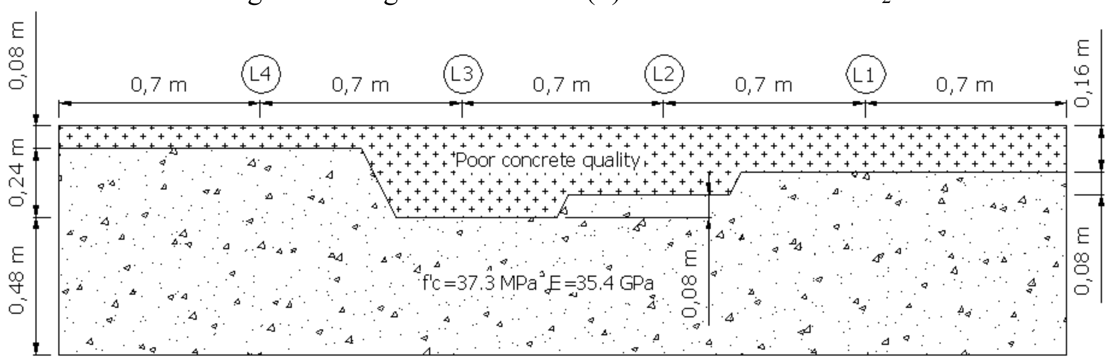


Figure 3. Longitudinal section (S) in concrete volume V_3

Table 1. Characteristics and aims of measurements on the concrete volumes

Volume #	Characteristics	Measurement Aims
V_1	Homogenous Discontinuity (Styrofoam leached by acetone)	Homogeneity test Localization of discontinuity or void
V_2	Three stratified layers with different mechanical properties and thicknesses	Estimation of layer thicknesses and the shear wave velocity profile
V_3	Poor concrete quality simulating freeze-thaw cycle deterioration on the top layer	Estimation of the deteriorated depth
V_4	Horizontally cracking planes	Detection of fissuring planes in the near surface concrete zone

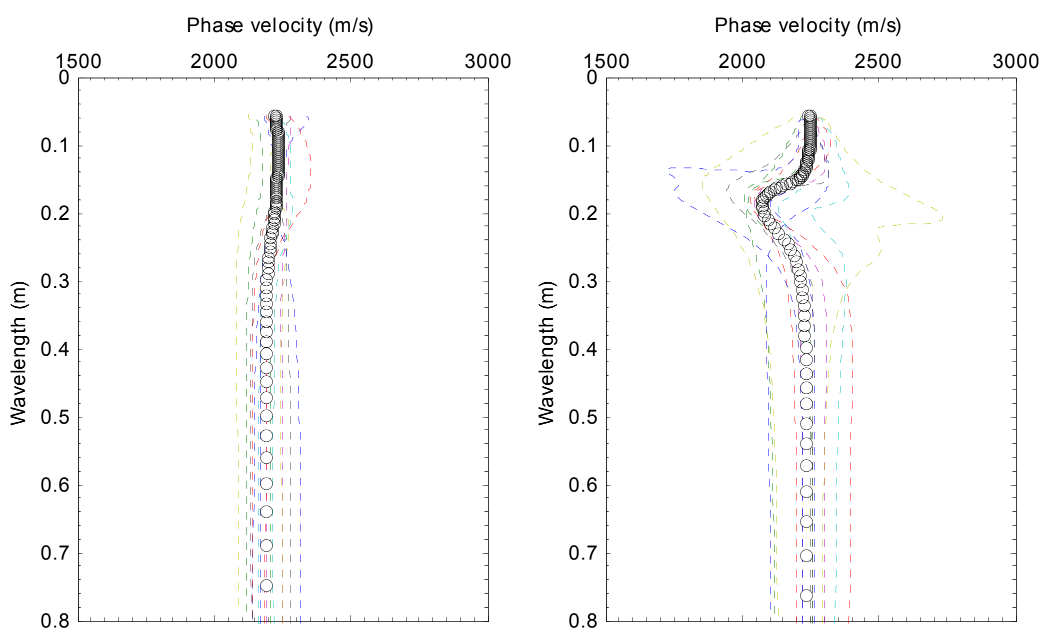
Table 2. Configurations of measurement tests

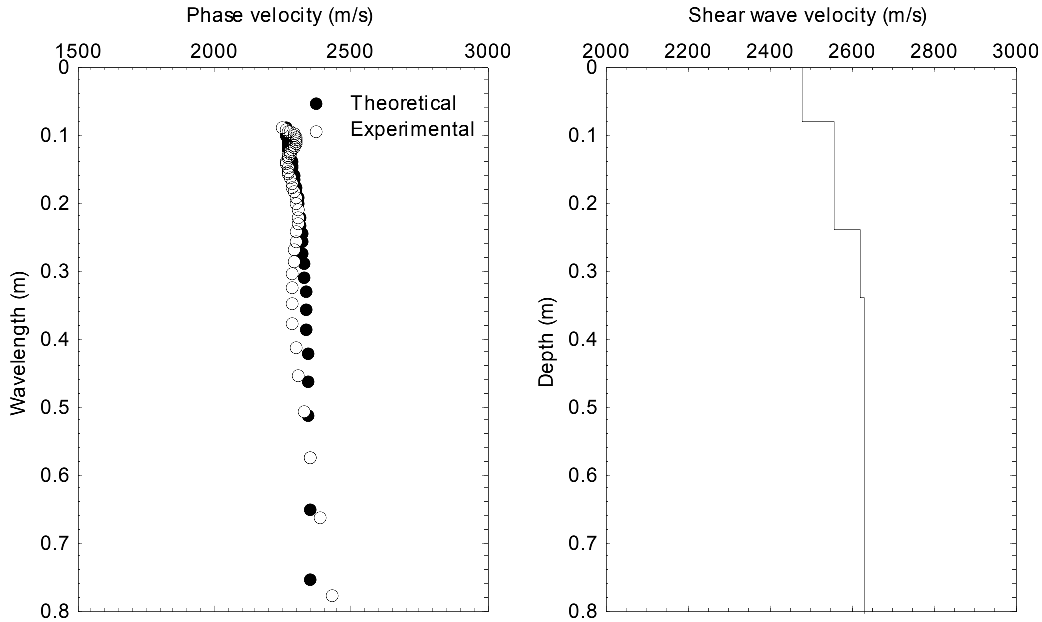
Volume #	Array	Receivers type	Source	SR_1 (cm)	R_iR_{i+1} (cm)
V_1	6	50 kHz Piezoelectric	50 kHz Piezoelectric	45	15
V_2	30	4396 B&K with 49 kHz natural frequency	Steel balls Ø 8 mm and Ø 13 mm Steel hammer 250 gr.	20, 20, 20	4
V_2, V_3, V_4	6	4396 B&K with 49 kHz natural frequency	Steel balls Ø 8 mm and Ø 19 mm Steel hammer 250 gr.	15, 30, 45	15

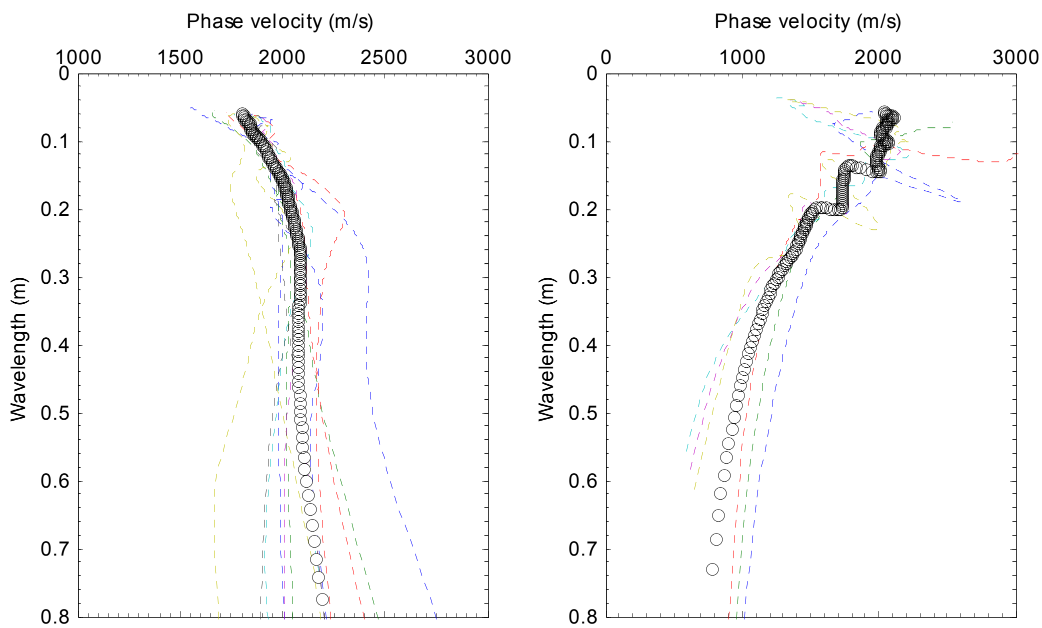
Results: Rayleigh wave dispersion curves resulting from two different signal processing techniques are plotted for each concrete volume. In the first method, collected data from the six receivers test series on measurement lines (L_1, L_2, L_3 and L_4) for all concrete volumes are treated using the classical phase unwrapping method, after applying exponential or kaiser window on all signals of a given record.

Fifteen dispersion curves were computed from receiver couples on each six array measurement test. Calculated dispersion curves from receiver couples were averaged in order to reduce the contribution of higher Rayleigh wave modes. Resulting dispersion curve presents the variation of Rayleigh wave phase velocity as a function of wavelength at the mid point of the distance between the first and the last sensor. A filtering window was necessary to eliminate the noise and reflections containing in signals. Results in Figures 4 and 5 illustrate the concrete homogeneity and a void detection in the first volume V_1. Poor concrete quality and horizontally cracking planes were localized on the near surface zone of the third and forth concrete volume respectively as indicated in Figures 8 and 9.

The second signal processing technique used in this study is based on the frequency-wavenumber analysis of the wavefield data. The presentation of the wavefield energy in the frequency-wavenumber domain is used in geophysics to distinguish noise and different Rayleigh wave modes (Nolet and Panza 1976, Gabriels et al 1987, Al-Hunaidi 1996). Sufficient number of equidistant sensors is needed for this method. A two dimensional Fast Fourier Transform 2D-FFT converts the array measurements from the time-space domain to the frequency-wavenumber domain (Alleyne and Cawely 1991, Forchap and Schmid 1998). The spatial or the time record can be zero padded in order to obtain higher resolution necessary to determine more accurately the maximum energy crests. The identified peaks in the frequency-wavenumber plane present the different mode of propagation (Rayleigh modes, flexural modes) and they are used to estimate the corresponding wavenumbers. Rayleigh wave modal phase velocities inversely proportional to the estimated wavenumbers can be then calculated as a function of frequency. After extracting the Rayleigh wave fundamental mode, the shear wave velocity profile can be determined using forward modeling inversion process. This technique was adapted for the 30 receivers array measurements of the second volume V_2 to determine the different layer thicknesses. An experimental dispersion curve was calculated for the fundamental Rayleigh wave mode. This curve was compared to the theoretical one given by the forward modeling until stabilization of the inversion process. The inverted shear wave velocity profile can be directly related to the variation of the mechanical properties with depth for the concrete volume. Results in Figures 6 and 7 show clearly three stratified layers of various thicknesses and mechanical properties.







Discussion: The above results demonstrate the accuracy of Rayleigh waves in the diagnosis of different concrete pathologies. Figure 4 shows constant phase velocity profile on measurement line L_1 of the first concrete volume V_1. Similar results were shown in case of homogenous concrete quality for all measurement lines on this volume. Averaged dispersion curves indicate a Rayleigh wave phase velocity of 2200 m/s approximately for all wavelengths less than the 0.8 m thickness of the concrete volume. This value is referred to a good concrete quality of 40 MPa compressive strength and 35 GPa Young modulus as measured by laboratory mechanical tests. In the same volume V_1, the induced void was detected under the measurement line L_2. Figure 5 indicates a phase velocity shift from 2200 m/s to 2000 m/s for wavelengths varying between 15 and 25 cm. This 200 m/s shifting can be explained by the existence of a certain void at a depth of approximately 20 cm from the surface. It is caused by the dissipation of a part of Rayleigh wave propagating energy through the void. Phase velocities related to wavelengths less than 15 cm and greater than 25 cm were not influenced by the void and they have the same value determined on the other measurement lines of the concrete volume.

On the second volume V_2, the new signal processing technique based on frequency wavenumber analysis of the wavefield data was tested to determine the different thicknesses of the three stratified layers. In similar cases, the use of the classical SASW technique may leads to erroneous dispersion curves and ambiguities. Higher Rayleigh mode energies due to the concrete layering, reflexions and flexural modes due to the finite dimensions of the concrete volume were separated in the frequency wavenumber plane. Figure 6 shows the extracted experimental dispersion curve for the fundamental Rayleigh wave mode and the theoretical one after inversion. The variations of the phase velocity are not sufficient to distinguish the different layers using the obtained dispersion curve only. As illustrated in Figure 2, the three layers have different compressive strengths (17.3, 28.5 and 37.3 MPa) but close Young modulus values (27.3, 29.6 and 35.4 GPa). The small difference between the Young moduli of the three layers, are the main reason that variations in the phase velocities are not important. This result joins previous studies which demonstrated that Rayleigh wave dispersion curves in layered concrete structure, are strongly related to the Young modulus profile more than the compressive strength (Hassaim et al 2001, Al Wardany et al 2003). The final model (theoretical) obtained by the iterative inversion process in the Figure 6, shows a good agreement with the experimental phase velocity profile. The corresponding shear wave velocity profile determines clearly in Figure 7 three different thicknesses under the measurement line L_4. The different thicknesses are successfully determined on the other measurement lines of V_2 using this new method.

In case of the third concrete volume V_3, important contrast between the top layer poor concrete quality and the bottom layer was observed in Figure 8. The averaged dispersion curve calculated on the measurement line L_1 from the six array measurement test indicates a low phase velocity in the top layer for wavelengths less than 32 cm. This value corresponds to a top layer thickness of 16 cm. The similar tests made on the other measurement lines demonstrate also low phase velocity on the concrete surface and variation in the mechanical properties at a depth equal to half the wavelength. In general, for geotechnical applications, the depth for a phase velocity variation occurred at a given wavelength, can be empirically estimated as the half or the third the wavelength (Heisey 1981).

Figure 9 shows a downward stairs shape of the phase velocity profile, due to the existence of two horizontal cracking planes under the measurement line L_1 of the forth concrete volume V_4. High frequency Rayleigh waves propagate near the concrete surface with a phase velocity of 2000 m/s. First, a 300m/s phase velocity shift was observed at wavelength of 15 cm. It localizes an upper horizontal crack at a depth equal the wavelength. The phase velocity conserves after the new value of 1700 m/s, then it decreases continuously at wavelength equal to 20 cm, indicating the existence of the second cracking plane at this depth. This multichannel phase unwrapping method used in this study demonstrates also high potential to localize horizontal cracking planes in the near surface concrete zone.

Conclusions: Based on the SASW method, advances in the determination of more robust resultant dispersion curve using a limited number of sensors (six accelerometers) were presented in this paper. This way of analysis aims to make easy test setup and to give more reliable results: there is no need to inverse the source position and to change the distance between receivers as required for the SASW test setup. Accuracy of this approach was approved to test concrete homogeneity and to detect poor surface concrete quality, voids, and horizontally cracking planes on concrete volumes. A new multistation Rayleigh wave method was developed in this study for concrete non destructive testing. The method considers a 2D-FFT transformation of the wavefield energy from the time-space plane to the frequency-wavenumber domain to identify existing Rayleigh wave modes. The extracted fundamental mode will be inverted using forward modeling to determine the appropriate shear wave velocity profile. This technique may be used when there is multimode propagation of Rayleigh waves through layered system. Comparison of the experimental and theoretical dispersion curve shows excellent agreement and reliable model. The proposed new method demonstrates high potential to characterize concrete stratification and determine thicknesses ever if variations in Young modulus profile are small.

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