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ULTRASONIC SURFACE WAVE IN CONCRETE: SENSITIVITY ANALYSIS OF PHASE VELOCITY DERIVATIVE

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ABSTRACT

Ultrasonic Surface Wave Methods are used to analyze impacts of small variations on different observables in a two-layer concrete medium. Rayleigh wave phase velocity derivative is proposed as a new observable and its behavior is analyzed and compared to classical observables qualitatively and quantitatively. A higher sensitivity of phase velocity derivative is observed and concrete slabs with various thicknesses and moduli are built to validate experimentally the numerical results.

NOMENCLATURE

i	Number of layers in a multi-layer model.
V_{s_i},V_{p_i}	Shear and compressional velocities at ith layer.
h	Layer thickness.
ρ_i	Density at ith layer.
ν	Poisson's ratio.
λ	Wavelength.
V_{ph},V_g	Phase and group velocities of Rayleigh waves.
$\partial_f V_{ph}$	Derivative of V_{ph} with respect to frequency.
$(\Delta X)_{norm}$	Normalized variation of observable X: $(\Delta X)_{norm} = \frac{X^{var}-X^{ref}}{X^{ref}}$. Observable X can be V_{ph}, V_g and $\partial_f V_{ph}$.
$\alpha(V_s)$	Shear velocity variation ratio: $\alpha = \frac{V_s^{var}-V_s^{ref}}{V_s^{ref}}$.

INTRODUCTION

Non-destructive techniques are widely used in civil engineering to evaluate structures properties and detect internal damages or material deteriorations in a non invasive way. For example, Electrical Resistivity Tomography for water gradient estimation [1] and ultrasonic Surface Wave Method (SWM) to recover mechanical properties on concrete [2]. But, traditional SWM can not accurately assess small variations in the medium, typically when variation ratio $\alpha \leq 5\%$ [3]. In this work, we use ultrasonic surface waves, to analyze small variations in a two-layer medium **Tab. 1**. However, classical observables (V_{ph} and V_g) are not sensitive enough to estimate small variations of medium, especially when variations occur at deep layer [3]. To overcome this limitation, we propose a new observable, which is the derivative of Rayleigh waves phase velocity with respect to frequency $\partial_f V_{ph}$. The behavior of this observable in the case of small variations in the environment is first qualitatively analyzed and then its sensitivity is quantified and compared to those of conventional observables. In the first part of the study, model shear velocities are changed in a small range to simulate medium small variations, because among the parameters of the model V_p, V_s, ρ, surface waves are more sensitive to shear velocity variation. Another parameter which attracts attention in civil engineering is layer's thickness, e.g., for tracking water penetration in cover concrete by combining the approach with electromagnetic investigation methods. Therefore, in the second part, the model parameters remain the same, we only assume that the thickness of the upper layer changes $h_1 \in [4, 20]\,cm$.

TABLE 1. TWO-LAYER MODEL OF CONCRETE.

layer	$h\ [cm]$	$V_p\ [m/s]$	$V_s\ [m/s]$	$\rho\ [kg/m^3]$	ν
1	8	3000	1750	1800	0.24
2	∞	3500	2095	2400	0.22

QUALITATIVE ANALYSES OF SMALL VARIATIONS

In the following, we qualitatively analyze the impact of small variations on the usual and new observables from the reference medium **Tab. 1**.Shear velocity and layer thickness variations are considered. Phase and group theoretical dispersion curves are calculated with the free software Geopsy, from which phase velocity derivative is deduced.

V_{s_2} variation: When variations occur at deep layer, as shown **Fig. 1**, the medium's variations are more and more significant for longer wavelengths in both V_{ph} and V_g dispersion curves visualization. This feature implies that it is necessary to access the observable at low frequencies, which can be difficult because dispersion curves are less resolved at low frequencies and require a longer measurement device. In opposite, the normalized variation of $\partial_f V_{ph}$ reaches maximum value at $\lambda \approx 10h_1$. This result means that the new observable $\partial_f V_{ph}$ can detect small variations in the deep medium in a much smaller wavelength range (or relative higher frequency range) than the classical observables.

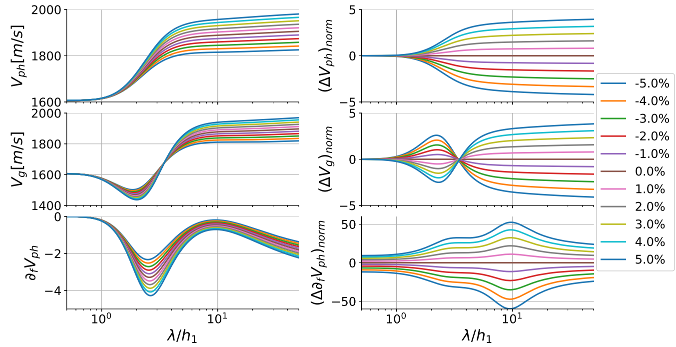

FIGURE 1. DISPERSION CURVES OF V_{ph}, V_g and $\partial_f V_{ph}$ FOR $\alpha(V_{s_2}) = 0$ AND $\alpha(V_{s_2}) \in [-5, +5]\%$. ON THE RIGHT COLUMN: $(\Delta X)_{norm}$.

Depth variation: When the model parameters are unchanged, the start and end points of the dispersion curves of the phase and group velocities are approaching the same value, and variations of upper layer thickness only cause changes in the slope of the dispersion curve (**Fig. 2**, left column). For the dispersion curve of the derivative of phase velocity, variations in thickness causes a change in values and positions of the minimum, but the appearance and trend of the dispersion curve have not changed significantly. Interestingly, when the dispersion curve is presented with normalized wavelength, phase and group velocities for different upper layer thicknesses coincide with each other, and minimum values of $\partial_f V_{ph}$ dispersion curves are in the same λ/h_1 position (**Fig. 2**, middle column). The misfit function in the inversion process, which calculates the difference between two dispersion curves, is defined as the average value of L2-norm normalized difference in the frequency range of interest. In **Fig 2** when $h_1 < 8mm$, the instability is observed as $\partial_f V_{ph}$ tends to zero at small wavelengths. This instability should be carefully treated when using the new observable in inversion calculation.

QUANTITATIVE ANALYSES OF SMALL VARIATIONS

Sensitivity curves are calculated for the three observables in order to understand the dispersion curve behaviors under medium variations. The partial derivative of V_{ph} with respect to the shear velocities is calculated analytically [4] and sensitivity curves of V_g and $\partial_f V_{ph}$ are calculated numerically (**Fig 3**). As expected, the sensitivities of V_{ph} and V_g to shear velocities occur at small and large wavelengths, respectively. As for $\partial_f V_{ph}$, maximum sensitivities for V_{s_1} and V_{s_2} are both around $\lambda/h_1 = 2.75h_1$.

CONCLUSION AND PERSPECTIVES

In a two-layer medium, the new observable $\partial_f V_{ph}$ is more sensitive to small variations of shear velocity and depth variations. This result makes it possible to consider the use of this new observable to quantitatively determine small variations in shear velocity and interface depth in the medium. These slight changes are particularly sought in the monitoring of civil engineering structures. Thus, the next steps, currently being processed, focus on the experimental validation by ultrasonic measurements on concrete slabs and resin blocks **Fig. 4**.

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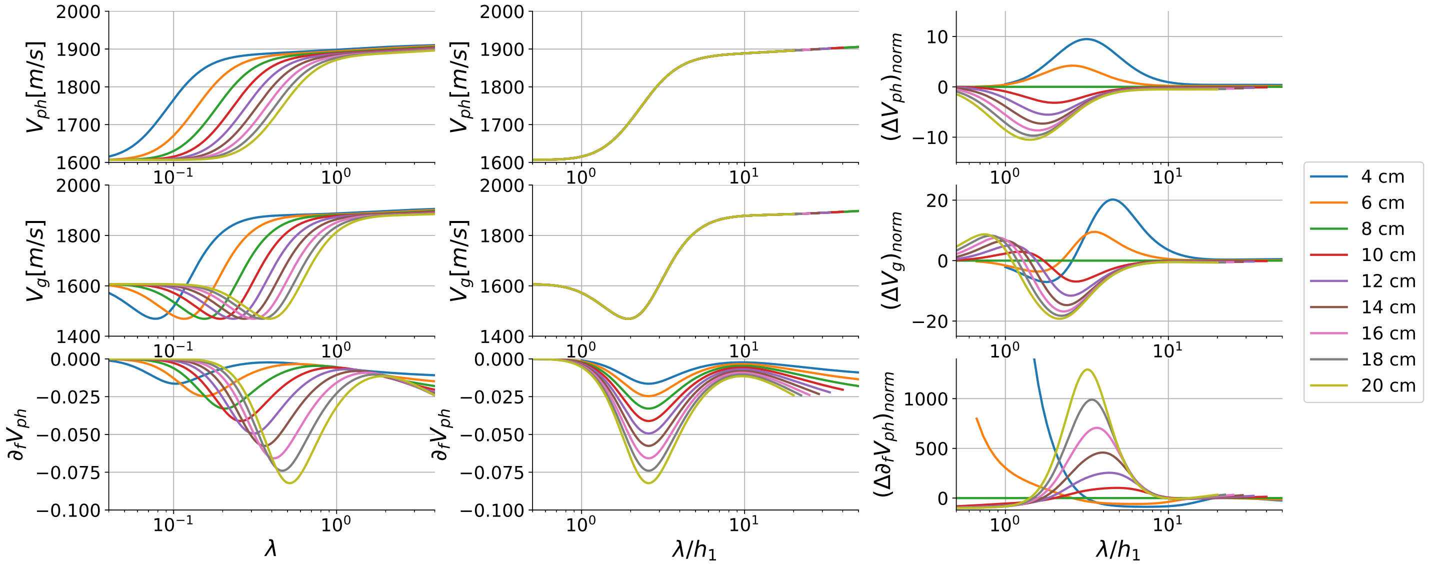

FIGURE 2. DISPERSION CURVES OF V_{ph}, V_g and $\partial_f V_{ph}$ FOR REFERENCE MEDIUM $h_1 = 8\,cm$ AND VARIATION MEDIUM $h_1 \in [4, 20]\,cm$.

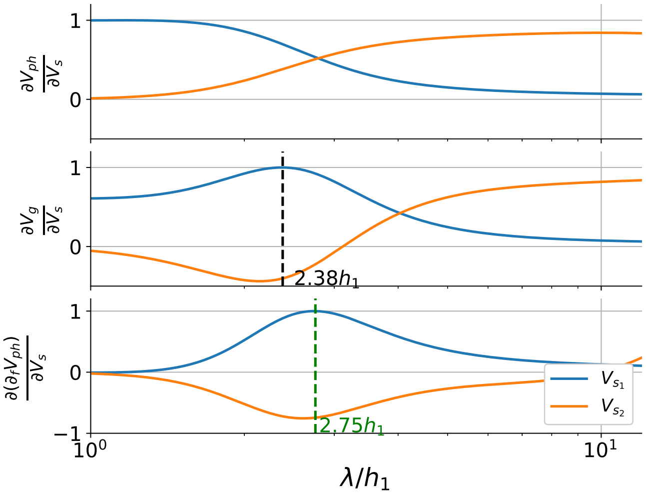

FIGURE 3. SENSITIVITY CURVES FOR V_{ph}, V_g AND $\partial_f V_{ph}$ WITH RESPECT TO SHEAR VELOCITY OF EACH LAYER.

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FIGURE 4. ULTRASONIC MEASUREMENTS ON CONCRETE.

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