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# RAYLEIGH WAVE PHASE VELOCITY – A NEW APPROACH APPLIED TO MONITORING ENGINEERING STRUCTURES

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**Abstract** – A new approach for phase velocity analysis of Rayleigh waves is presented, whose main characteristics are simplicity, objectivity, sensitivity and accuracy of the results obtained in the stability monitoring of engineering structures such as dams and tailings piles, as well as mine pits. The importance of identifying and spatially locating small velocity variations and their relationship with changes in the mechanical properties of structures capable of modifying their stability is discussed. The seismic data are transformed to the frequency domain and the presented technique extracts the signal amplitude curve as a function of the velocity relative to the selected frequency and accurately defines the phase velocity in the dispersion zone. The information obtained is positioned in time and space, with the depth being estimated based on the signal wavelength.

**Keywords** – Geophysical Monitoring, Dams, Piles, Pits.

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## 1. INTRODUCTION

This work aims to present a new, simple and objective approach to analyze the phase velocity of Rayleigh waves, using multichannel passive seismic information, aiming at monitoring variations in the S-wave velocity. The main objective of the work is to develop a technique capable of allowing the accurate monitoring of small variations (< 5%) in the phase velocity of the Rayleigh wave, in engineering structures such as dams and tailings piles, as well as mine pit slopes. Monitoring small velocity variations in this type of terrain becomes increasingly important due to climate changes that are normally associated with variations in groundwater levels and fluid percolation in the unsaturated zone, the effects of which can potentially lead to collapses in the structures. Traditional methods of inverting dispersion curves do not always have sufficient precision to detect small changes in the environment, given the limitations that may be related to the steps of extracting the dispersion curves, as well as the inversion processes (Wang et al., 2021).

The S-wave velocity is the dominant property (around 92%) that influences the dispersion curve of surface waves in the high frequency range, greater than 5 Hz (Sheriff & Geldart, 1985; Stokoe et al. 1994), so it is possible to assume that the variations in the phase velocity of Rayleigh waves fundamentally reflect variations in the S-wave velocity in a terrain.

Traditional methods of inverting dispersion curves are important because they allow the definition of a spatial distribution pattern of S-wave velocity values and the correlation with the geology of a structure, necessary for the diagnosis of dams, piles and pits. The S-wave velocity values are directly related to the shear modulus (G), which characterizes the materials by their rigidity and their resistance to transverse deformation under stress, and is defined by G = ρ.Vs2, where ρ is the density and Vs the S-wave velocity in the medium. Likewise, they allow the characterization of materials in terms of the degree of compaction (Park, 2023) and their liquefaction potential (Andrus et al., 2004). Values lower than 200 m/s are normally associated with the presence of soft soils (Park, 2023), while the upper limit Vs for the S-wave velocity, with real liquefaction potential of the medium, varies between 200 m/s and 215 m/s and can be estimated by the relation Vs = 215 – 0.5(FC-5), for 5% < FC < 35%, with FC being the average fines content in percentage (Andrus et al., 2004). Determining the profile of the variation of the S-wave velocity at depth also enables the calculation of the local Vs30, which consists of the average velocity of the S-wave up to 30 meters in depth and allows the classification of the terrain according to the criteria established by the IBC – International Building Code (2012), which deals with the technical provisions and minimum requirements necessary to guarantee the safety of engineering projects.

However, monitoring small variations over time and space is essential for monitoring changes in the environment that may be modifying the stability of structures. Small variations in the S-wave velocity may be associated with changes in pressure in cracks (Nur, 1971), fluid saturation (O'Connell & Bodiansky, 1974) and fluid pressure in pores (Brenguier et al, 2014) in the subsurface. De Wit & Olivier (2018) related a 0.3% reduction in the S-wave velocity in a dam to an increase in the degree of saturation due to rainfall, causing an increase in the pressure of the fluids in the pores, with the consequent opening of microcracks. Similarly, De Wit & Olivier (2018) associated a greater reduction in the S-wave velocity, of the order of 2%, to the period of greatest rainfall intensity, with an increase in the water level of 30 cm, observed in the piezometers.

Monitoring these small variations in velocity and their spatial and temporal locations, done with precision, is very important for understanding the stability of the monitored structures and justified the development of the technique for analyzing the phase velocity of Rayleigh waves for each selected frequency, which we are presenting in this work.

## 2. ABOUT THE NEW APPROACH TO ANALYZING THE PHASE VELOCITY OF THE RAYLEIGH WAVE

Continuous phase velocity analysis can be performed by collecting a large number of passive or active seismic records daily, using a set of twenty-four 4.5 Hz geophone channels, spaced 2.5 meters apart, permanently deployed in the area under investigation, in continuous operation. Figure 1 shows an example of a collected seismic record.

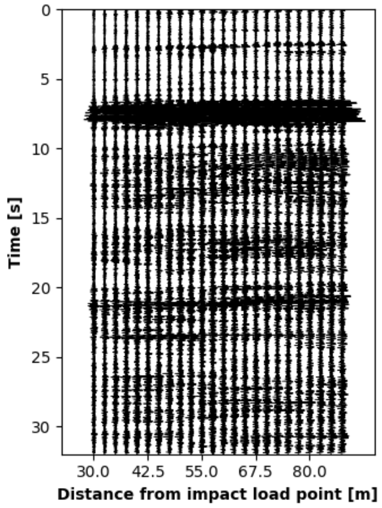


Figure 1. Example of passive seismic recording with 24 channels.

The seismic records are transformed to the frequency domain (Olafsdottir et al. 2024), and the band of interest for analysis, corresponding to dispersive waves, is selected (Figure 2).

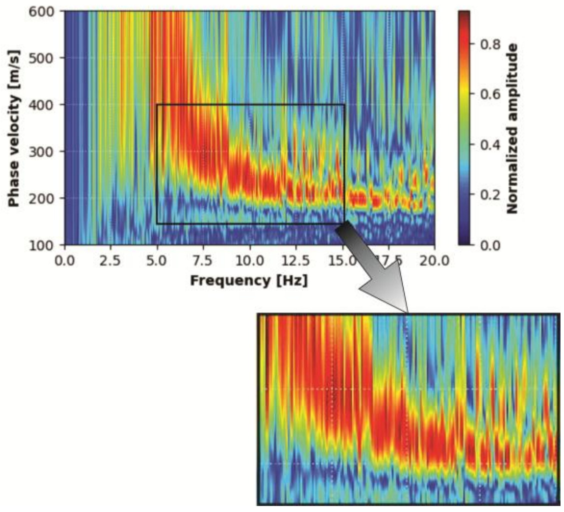


Figure 2. Seismic record in the frequency domain, highlighting the signal range of dispersive waves.

After operations performed in the frequency domain, aiming at signal optimization, the phase velocity analysis is performed for each selected frequency, with extraction of the signal curve in the area of interest (Figure 3). For each frequency, a standard reference curve is extracted, the initial phase velocity is defined and its variations are monitored over time. The depth of the results obtained is estimated as a function of the wavelength, so that the results obtained are positioned in time and space, throughout the monitoring process of the investigated structure.

The signal peak in the area of interest defines the phase velocity of the Rayleigh wave (Figure 3), while the zero value in the graph of the signal derivative in relation to the phase velocity (Figure 4) precisely defines the phase velocity.

The variation over time, indicating possible changes in the stability of the structure, is obtained by comparing curves over time with the standard curve defined for each selected frequency.

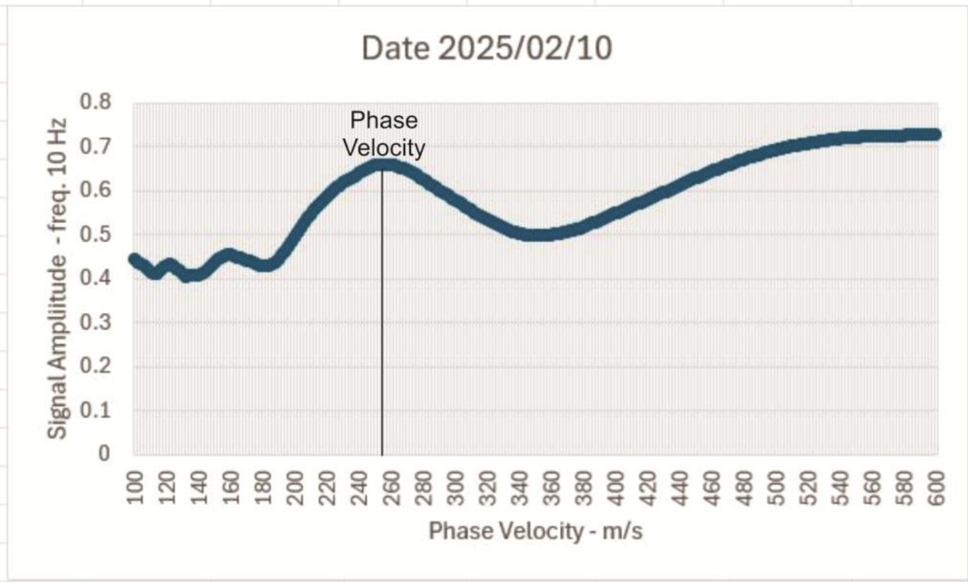


Figure 3. Signal curve at the selected frequency, with peak amplitude at phase velocity.

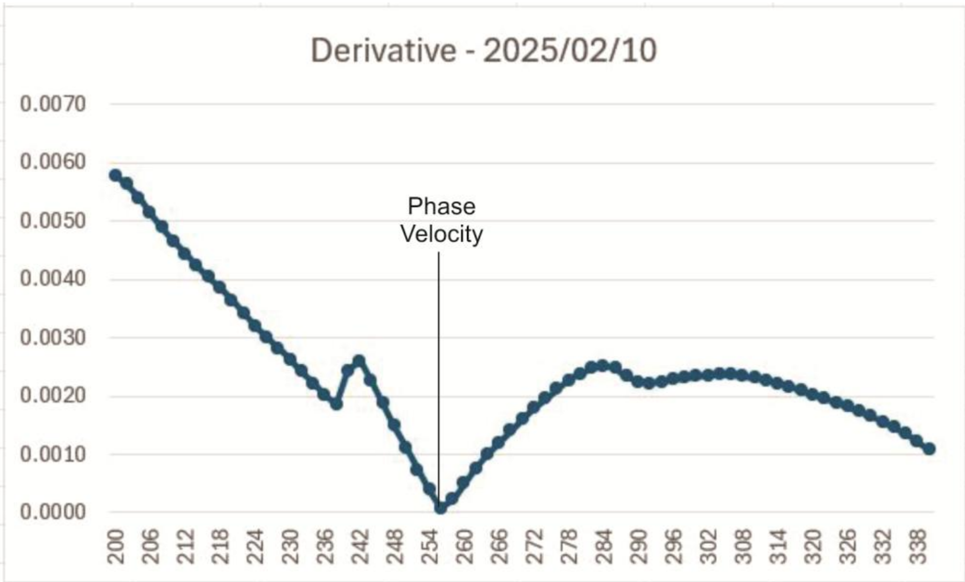


Figure 4. Derivative of the signal as a function of phase velocity, with zero at the peak of phase velocity.

## 3. RESULTS AND DISCUSSIONS

In traditional methods of inverting dispersion curves, the analysis of variations in the velocity of the S wave through the periodic generation of models correlated with geology allows monitoring and identification of trends in variation over time, with a predicted increase in the risk of instability in the structure, in case of Vs approaching the reference value, normally considered 200 m/s (upper limit for loose material (Park, 2023) and material with liquefaction potential (Andrus et al., 2004). In the case presented here, the monitoring carried out through the analysis of the phase velocity of the Rayleigh wave, identifying and positioning, in time and space, small variations in velocity, allows the interpretation that the variations may be the effect due to changes in pressure, degree of saturation and fluid pressure in the pores (Nur, 1971, O'Connell & Bodiansky, 1974, Brenguier et al., 2014 and De Wit & Olivier, 2018).

Figure 5 shows an example of a phase velocity variation of -2.3%, for the selected frequency of 10 Hz, which occurred between 2025/02/10 and 2025/02/19, at the dam under investigation. During this period, a change in phase velocity was observed, going from 256 m/s to 250 m/s, at an estimated depth of around 13 meters (half the wavelength). This variation could be related to the more intense rainfall that occurred in the previous period.

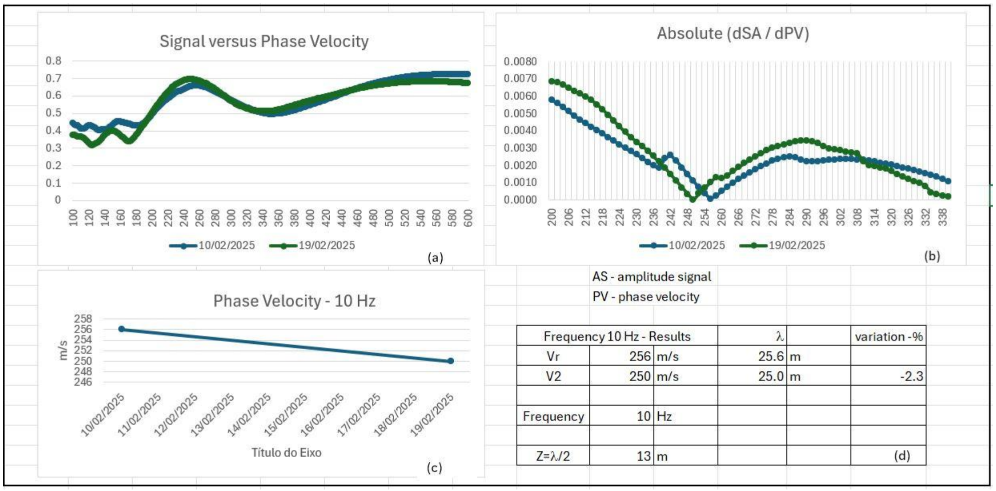


Figure 5. Example of the phase velocity signal of the Rayleigh wave defined for 02/10/2025 and 02/19/2025, with a variation of -2.3% in the period. (a) signal as a function of the phase velocity for a selected frequency of 10 Hz, on both dates, the two peaks indicate the phase velocities; (b) derivative of the signals as a function of the phase velocity, with zero values at the peak of phase the velocities; (c) graph of the variation of phase velocity in the period and (d) table with a summary of the results defined in the analysis.

## 4. CONCLUSIONS

The approach presented here for analyzing the phase velocity of Rayleigh waves allows for the monitoring with good precision of small variations in velocity, localized in time and space, which are difficult to detect using the traditional data inversion methodology. These small variations reflect changes in the environment that may be related to the stability of the monitored structures, such as the degree of saturation, pore fluid pressure, variations in the water table and fluid percolation.

The application of the analysis technique is possible from a permanent monitoring system with a large number of receiver channels, which allows for the continuous passive collection of seismic data, making it possible to obtain a large amount of daily information.

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