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Techniques for mode separation in Rayleigh wave testing

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ABSTRACT

The spectral analysis of surface wave (SASW) developed in the early eighties has opened the way to the use of surface waves for the definition of shear wave velocity profiles in soil deposits or pavement structures without the need of any borings or intrusion. The SASW testing procedure was designed to minimize the contribution of higher modes and thus assumes that the Rayleigh waves which propagate at the surface belong only to the fundamental mode. Several studies have however demonstrated that, in some conditions, higher Rayleigh modes can contribute significantly to the dispersion curve. Different tests configurations exist today to deal with Rayleigh mode problem by the use of an array of receivers. In spite of that, the SASW configuration remains attractive due to the limited number of receivers, as well as, the Rayleigh modes contributing in SASW records configuration can be identified by multiple-filter technique and isolated using time-variable filters. The proposed techniques are first validated by simulated records and then applied to SASW records obtained in the field. The study confirms that higher modes can participate and even dominate in SASW records. An important contribution of higher Rayleigh modes can also exist, even if the shear wave velocity increases regularly with depth. The higher Rayleigh modes can significantly affect the accuracy of the shear wave velocity profile if they are not properly identified and separated. A multi-mode inversion process is shown to be important to have an accurate soil characterization.

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1. Introduction

Shear wave velocity is used extensively to determine the small strain shear modulus for dynamic response analysis [1–3] and to some extent for the assessment of pavement structures [4,5]. The in-situ determination of shear wave velocity can be useful also in the characterization of granular deposits in terms of elastic properties and density [6].

The in-situ shear wave velocity (V_s) can be measured directly between two sensors placed in separate bore holes (*cross hole*) or in a single bore hole at depth and at ground surface (*down hole*). V_s can also be evaluated by the use of the surface Rayleigh waves (R-wave). The R-wave velocity has been utilized for a long time to provide information on the elastic properties of soils and pavements [7,8], since the measurements are made at the surface without the need of borings or intrusion in the deposit. One of the most important advantages in the use of the techniques based on the propagation of R-waves is the predominance of this wave at the surface, when generated by a vertical source.

Steady-state testing was the first R-waves vibration technique used for site investigation. The technique involves the detection of a monochromatic surface wave generated by the vibrator acting vertically. In order to evaluate the wavelength, Jones [7] used a single receiver moved progressively away from the source to find the successive positions at which vibrations were in phase with those at the generator. The wavelength (λ) was given by the distance between two such successive positions and the phase velocity (c) was evaluated by the relation:

$$c = f\lambda \qquad (1)$$

Abbiss [9] evaluated the wavelength by the difference in phase (ϕ in rad) between two receivers placed at a known distance d apart in line with a vibrator:

$$\lambda = \frac{2\pi}{\phi d} \quad \text{where} \quad \lambda < d \qquad (2)$$

The use of R-waves to characterize a soil deposit was earlier limited by the use of monochromatic sources and by the equivalent depth approximation (z_{eq}) in the inversion process ($z_{eq} = k_z\lambda$). k_z is a constant varying depending on the authors between 0.33 [10] and 0.5 [9,11]. The spectral analysis of surface waves (SASW, [4]) has allowed a faster interpretation to define a continuous shear wave velocity profile. Surface waves are generated by a polychromatic impact source and detected at two points situated at a distance d_1 and d_2 from the source. The configuration of the SASW test is shown in Fig. 1. To minimize the effect of body waves, Nazarian [12] suggests that the source to the near receiver distance (d_1) be equal to the spacing between receivers (d_2–d_1). The test is repeated for several receivers spacing to cover a large band of frequency or wavelength and in two directions to cover the effects of variability of the deposit. The phase shift between the two receivers (cross-power spectrum) is then evaluated by multiplying the FFT of the first signal by the complex conjugate of the FFT of the second signal. When the phase shift is unwrapped, phase velocity (c) and wavelength (λ) are evaluated from Eqs. (1) and (2). Based on experimental results, Heisey [10] proposed a filtering criterion suggesting that the acceptable wavelengths must be situated between $d/2$ and $3d$ (d is the receivers spacing). The total dispersion curve is then obtained by application of the same process for all spacings considered.

The transformation of the dispersion curve to a shear wave velocity profile (inversion) in the SASW method consists in comparing the experimental dispersion curve with a theoretical one based on the fundamental R-mode for a horizontally stratified medium consisting of N-layers.

The experimental dispersion curve is assumed to be representative of the fundamental Rayleigh mode. However, a number of experimental and analytical studies have demonstrated that, in some conditions, higher modes can interfere with and even dominate the fundamental Rayleigh mode [7,13–17] and thus significantly affect the dispersion curve even if the source and sensors locations in the standard SASW procedure are designed to minimize the higher modes contribution. The unknown contribution of higher modes in the experimental dispersion curves appears as the principal source of inaccuracy in the SASW method. There is today consensus that methods of investigation based on surface waves should assume that higher Rayleigh modes could contribute to the dispersion curve and that techniques should be used to separate or eliminate the contribution of these higher modes before proceeding with inversion [3,18,19]. Different tests configurations exist today to deal with Rayleigh mode problem by the use of an array of receivers (MASW, *f–k*). In spite of that, the SASW remain attractive due to the limited number of receivers.

The purpose of this paper is to propose an alternative techniques to identify the modes of Rayleigh waves propagating at the surface of soil deposit, to assess the interference of higher modes on the dispersion curve and thus to verify the assumption that the fundamental mode dominates when sensors and source are located as recommended in SASW procedures. Modes identification techniques will first be demonstrated on simulated signals and then applied to SASW fields records obtained in this study at an experimental site (Temiscouata, Quebec). Steady-state vibration tests were also performed at the Temiscouata site.

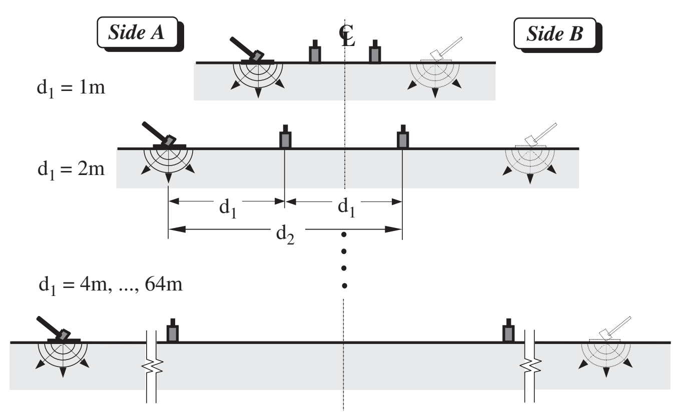

Fig. 1. SASW test configuration.

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