Detection of Fissures in Desiccated Soils Using Spectral Analysis of Rayleigh Waves

Bernardo Caicedo, Julián Tristancho, and Luc Thorel

Abstract. Retrospective analysis of surface waves is a non destructive method that is widely used nowadays. This paper focus on the application of surface waves as a tool to detect fissures in desiccated soils. As a first approach, this paper presents the results of tests carried out using compacted Speswhite kaolin in unsaturated state and artificial fissures.

Keywords: fissures detection, Rayleigh waves, physical modeling, SASW.

1 Introduction

Geophysical methods have been used to characterize soils since 1960. Among these methods, the analysis of surface waves has received considerable attention for example to study the deterioration of materials (Wardany et al 2003) the evaluation of the sub grades of pavements and to assess the dynamic properties of soils, (Bertel 2006). Mechanical waves propagate in an elastic half space following two main propagation patterns: body waves and surface waves.

Body waves propagate in all directions within the half space, and in the case of homogeneous materials the propagation front is spherical. These body waves are

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classified in primary waves (P) which are compressive waves and secondary waves (S) which are shear waves.

On the other hand, surface waves propagate along surfaces having high contrast in stiffness (free surface or different layer in the soil profile). These waves propagate at lower velocity than shear waves, and their amplitude decreases with the distance (r) from the source with lower rate than body waves. In fact, surface waves amplitude decreases proportionally to $\lambda / \sqrt{r}$, although the so called far field terms of the body waves decreases proportionally to λ / r^2 - the near field ones attenuates even more rapidly with λ / r^3. There are two types of surface waves: Rayleigh and Love waves, Rayleigh waves propagate only at the free surface although Love waves propagate within the interface between materials of different stiffness.

This paper presents laboratory tests of surface waves propagation carried out on reduced scale models. The retrospective analysis of the Rayleigh waves gives some inputs to assess fisuration on soils. This paper describes the characteristics of Rayleigh waves, then the experimental setup is described and finally the results are presented. The main purpose of this study is identifying fissures on desiccated soils however as a first approximation this work focuses on artificial fissures.

2 Rayleigh Waves

Rayleigh waves have low velocity, low frequency and high amplitude. When a compression source is used to produce surface waves, around 2/3 of the energy is transformed in Rayleigh waves. Furthermore Rayleigh waves propagate in a half space following a dispersive pattern, it means that waves of higher wavelenghts and therefore lower frequency propagate affecting deeper soil layers than short wavelengths and high frequency waves.

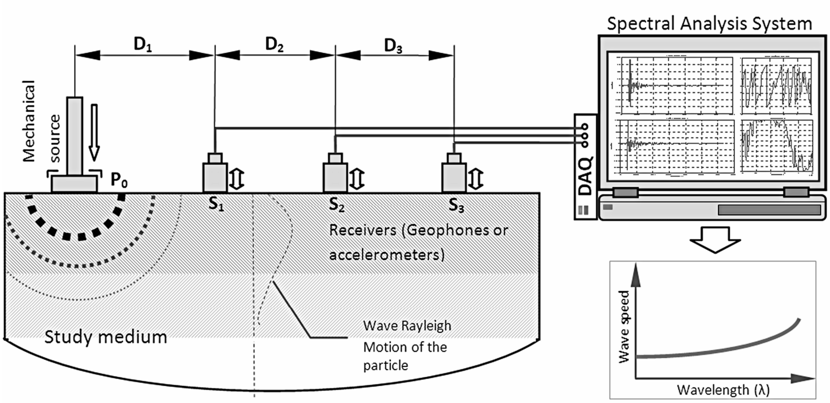

Fig. 1. Schematic configuration of the experimental setup to measure the propagation of surface waves.

The dispersive propagation characteristic of Rayleigh waves is at the base of the SASW method (Spectral Analysis of Surface Waves). This method was developed by Nazarian & Stokoe, 1983 in its early development stage it was used to characterize pavement structures but the possibilities of applications increase rapidly. Nowadays the SASW method is used widely to characterize the dynamic properties of soils in situ, to evaluate the liquefaction susceptibility, and others, Stokoe et al., 2004.

3 Experimental Setup

The experimental setup used in this research is presented in fig. 1. This figure shows the different components of the system, the mechanical input is created by a Piezoelectric actuator (P_0), this actuator have a piezoelectric load cell to measure the input compression wave. The system has a set of broad spectrum accelerometers (S_1, S_2, S_3, etc.), these accelerometers are located at different distances from the input source (D_1, D_2, D_3, etc.). The accelerometers and the load cell are linked to a data acquisition system allowing high frequency measurements.

The mechanical input produces P, S and Rayleigh waves that propagate from $P_{0,}$ fig. 1. However body waves decrease at higher rate than surface waves, as a result after some distance the recorded signals are made mainly by surface waves. On the other hand for distances close to the source the recorded signal have both body and surface waves, this is the near field effect. It is important to note that to avoid the presence of body waves on the recorded signals the first accelerometer must be located at a distance that guarantee the dissipation of body waves, Murillo, 2006. The fig. 2 presents the wave lengths for different frequencies and for different shear wave velocities, showing the relation between frecuency, wavelength and stiffness.

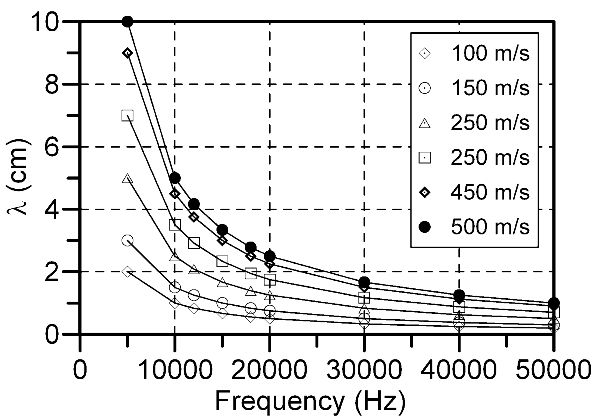

Fig. 2. Exploration wavelength values as a function of the shear wave velocities of soils and the frequency of the signal (Murillo, 2009).

3.1 Materials and Instrumentation

The soil tested was compacted kaolin Speswhite produced by Imerys. This soil was mixed with water to achieve the optimum water content of the Proctor Standard compaction tests (29.3%), then a vertical stress of 2 MPa was applied and the consolidation process was verified using the Asaoka method(Asaoka, 1978). Once compacted, the soil suction was 800 kPa, Murillo, 2006.

The mechanical source is a piezoelectric actuator type Cedrat PPA40M, with this actuator it is possible to impose sinusoidal or impact waves. This kind of actuator needs a high voltage level to achieve the required load and stroke (i.e. displacements up to 40 μm are achievable using -20 to 150V). The signal used to experimental procedure was an impulsive signal (type step). An example of the input signal used on piezoelectric actuator is show in fig. 3.

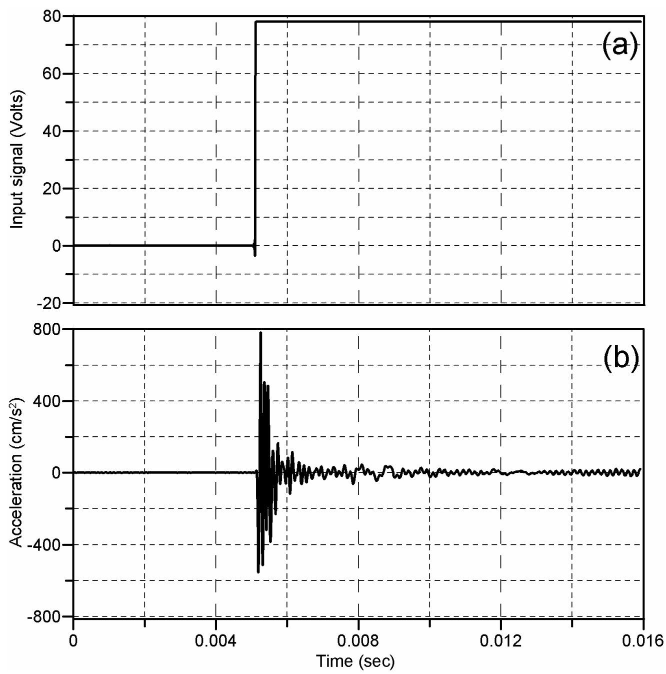

Fig. 3. Example of input signal for experimental tests. a) Input signal of piezoelectric actuator and b) Accelerometor signal to 0 cm from piezoelectric actuator.

The set of accelerometers used for the tests were PCB 352 A10. These accelerometers are uniaxial and have a broad frequency bandwidth (from 2Hz to 10 KHz), their acceleration range goes up to 500g and their weight is less than 1 gr. These accelerometers are located at the surface of the soil as shown in fig. 2.

The data acquisition system used for the tests was the system CAREMBA (Chaîne d'acquisition Rapide Embarquée) developed at the IFSSTAR in Nantes France. This system has three VME cards with 32 channels with independent amplification factors imposed by software, the A/D.

The sampling frequency is a key point to analyze the signals. According with the Nyquist theorem, (Smith, 1999), the frequency band available to carry out the analysis is limited to the half of the sampling frequency. Therefore to avoid any problem with the frequency analyses related to the aliasing, the sampling frequency used was higher than 50 kHz.

4 Experimental Procedure

To perform the tests, the soil was compacted applying a static compressive stress of 2 MPa in a cylindrical mould (30 cm in diameter). Then the set of accelerometers were placed at the surface of the mould. Four accelerometers were used: one placed over the plate that applies the load and three other accelerometers were placed with 50 mm of separation between them, fig. 3. Afterwards the fissures were created artificially at the middle distance between accelerometers, the depth of the fissures was increased progressively from 8 mm to 34 mm and measures were made for each depth.

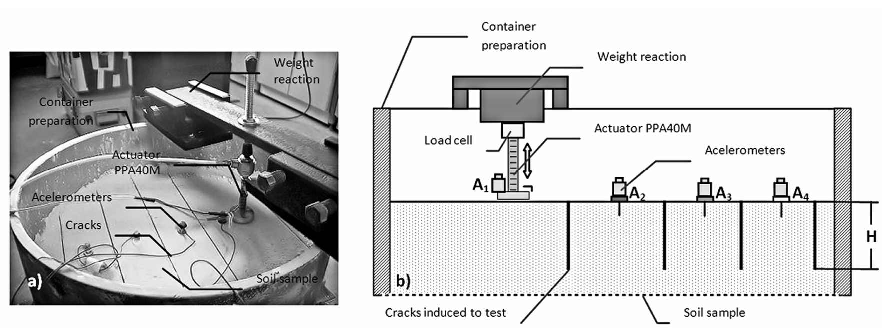

Fig. 4. (a) Experimental setup, (b) details of the location of fissures and accelerometers.

For each fissure a spectral analysis was carried out using the Fourier transform as shown in fig. 4. This figure presents the Fourier transform measured by the same accelerometer (accelerometer A_2 in fig. 3, located 10 cm from the piezoelectric actuator) for different depths of the artificial fissures. Depending on the depth of the fissures the surface waves are affected as follows: shallow fissures affect the propagation of the waves having shorter wavelength and higher frequencies; as the depth of the fissure increases the frequency band where the propagation is affected goes to lower frequencies. It is possible to calculate the frequency band where the propagation is affected, this is possible knowing the Rayleigh wave velocity and assuming that the penetration depth of the surface waves correspond approximately to its wave length, these bands for each fissure depth are presented in fig. 5. These results show that the fissures act as a filter for surface waves; this could be a new possibility to identify fissures in desiccated soils.

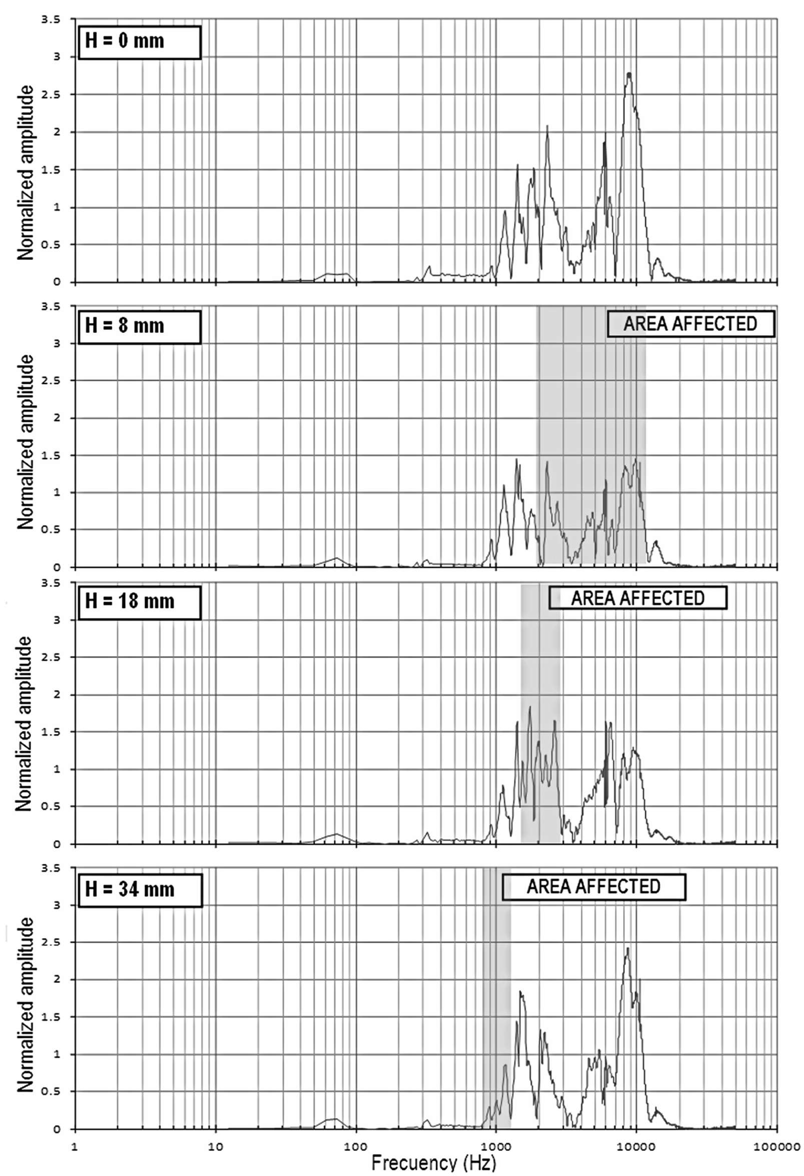

Fig. 5. Example Fourier spectrum for each depth of the fissures.

The table 1 is a summary of the results of the experimental tests. The first column is the fissure depth, the second column is the frequency associate with the wavelength equal to fissure depth and a wave velocity of 220 m/s (Mean Rayleigh wave velocity for material tested. Murillo, 2006) and the third column show the frequency band that was affect in the spectral analysis (fig. 5).

Table 1. Summary of the results of the experimental tests.

Crack depth (mm)	Frec. assoc (kHz)	Band affected(kHz)
8	27.5	2 – 12.0
18	12.2	1.7 – 3.0
34	6.5	0.8 - 1.1

5 Conclusions

The experimental study presented in this paper show the possibility of identifies fissures in soils using surface waves. The results show that the fissures act as a filter for the propagation of Rayleigh waves.

The results presented in this paper correspond to the first results concerning wave propagation in fissured soils; several points need further research to progress to an operational in situ method: the near field effect has an important influence on the quality of the measures, the effect of the suction and water content on the wave propagation on fissured soil, also improving the relationship signal/noise for long wavelength waves is necessary to identify deep fissures.

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