Laser-doppler Acoustic Probing of Granular Media with Varying Water Levels

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Laser-Doppler acoustic probing of granular media with varying water levels

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Abstract

Laboratory physical modelling and non-contacting ultrasonic techniques are frequently proposed to tackle theoretical and methodological issues related to geophysical prospecting. We used an innovative experimental set-up to perform laser-Doppler acoustic probing of granular materials with varying water levels to target near-surface hydrogeological applications. The preliminary results presented here show a clear influence of the water level on both first arrival times and dispersion of guided waves, and significant differences in terms of amplitudes. They validate the use of such approach to benchmark recently developed methods for water saturation detection in hydrogeophysics.

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Keywords: Granular materials; Laser-Doppler experiments; Analogue modelling; Seismic modelling; Water saturation; Hydrogeophysics.

1. Introduction

Laboratory physical modelling is frequently proposed with non-contacting ultrasonic techniques to study seismic wave propagation at various scales, with a wide range of applications in civil engineering (Ruiz and Nagy, 2004), near-surface geophysics (Bodet et al., 2005, 2009), exploration seismic (Campman et al., 2004; de Cacqueray et al., 2013) or seismology (Nishizawa et al., 1997). The non-contacting character of ultrasonic techniques and their high-density sampling abilities provide flexibility that gives the opportunity to simulate typical seismic records in the laboratory. Small-scale physical modelling applied to seismic methods is mostly performed using homogeneous and consolidated materials, such as metal and thermoplastics (Bretaudeau et al., 2011). However, when problematic of unconsolidated and/or porous materials have to be considered (for instance, to target near-surface exploration and hydrogeologic prospecting issues), there is an obvious need to study the propagation of seismic waves in more complex and realistic media. In the field of geological analogue modelling, several authors (Krawczyk et al., 2013) managed to mimic seismic prospecting acquisition techniques on water-saturated sandbox models, thus illustrating the great potential and

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flexibility offered by granular materials in terms of physical model construction. Bodet et al. (2010, 2014) recently addressed the ability of laser-Doppler experiments in the systematic characterisation of dry granular materials involved in geological analogue modelling, such as natural sands or glass beads (GBs). A methodology has been validated on an unconsolidated granular medium, perfectly characterised in terms of elastic parameters. A mechanical source and a laser-Doppler vibrometer were used to record small-scale seismic lines at the surface of the granular medium. Pressure-wave first arrival times and surface-wave dispersion were then inverted for one-dimensional (1D) pressure and shear-wave propagation velocity profiles with depth, which offered a good match with previously estimated properties of the probed medium. This experimental setup was also used successfully by Bergamo et al. (2014) to validate a new technique for extracting surface-wave dispersion lateral variations (Bergamo et al., 2012). In order to validate recently developed methods for water saturation detection in hydrogeophysics (Pasquet et al., 2015), similar experiments are performed here to monitor granular media with varying water levels. Beside a visual control of the water level, Time Domain Reflectometry (TDR) measurements are also proposed to follow the evolution of the water level during the acquisition and retrieve a profile of the water content with depth (Fratta et al., 2005).

2. Experimental set-up and data acquisition

For this study, we built a glass aquarium with dimensions 800 × 400 × 300 mm, with two 50-mm wide tanks installed lengthwise on both sides of the aquarium (Fig. 1). These two tanks are connected with the central part by two 15-mm high openings located at the tank bottom and covered with a metal sieve allowing for imbibing the granular medium from the bottom by gradually increasing the water level in the tanks. Glass beads with a diameter of 1000 μm were used to build the physical model (PM1). Thanks to the low cohesiveness of glass beads and their well classified size, we were able to ensure an homogeneous deposition of the GBs by simply pouring them into a sieve following a rotary movement sweeping all the aquarium (Bodet et al., 2014). The model is composed of GBs evenly distributed over a thickness of 255 mm. Based on the work of Bodet et al. (2014), the density of GBs could be approximated to 1600 kg/m^3. Similarly, Bodet et al. (2011) measured the hydraulic permeability values of glass beads with a similar granulometry (around $5000 \cdot 10^{-12}$ m^2). The use of such GBs thus ensured a homogeneous imbibition of the model from the bottom. For each acquisition, the water level was ultimately increased stepwise by filling the side tanks.

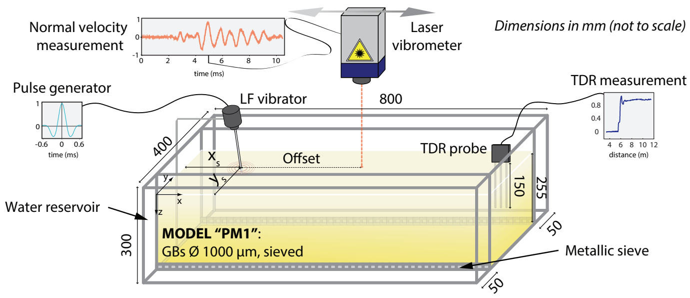

Fig. 1. Experimental set-up, geometry and parameters of the physical model.

The acquisition setup presented in Fig. 1 involved a laser-Doppler vibrometer allowing for recording the vertical particle displacement velocities at the surface of the granular medium excited by a mechanical source. In this study, the medium was mechanically excited by a metallic stick buried in the granular material and attached to a low frequency vibrator driven by a waveform generator. The force source signal was a Ricker pulse with its frequency spectrum centered on 1.5 kHz. Maintaining the source at the same position (x_s = 655 mm; y_s = 150 mm), the surface of the medium was scanned by the laser with a constant step (Δx = 5 mm). 100 traces were recorded with an oscilloscope along a profile oriented in the direction O_x, so as to retrieve 500-mm long profiles. For each trace, 50 stacks were performed with a sampling rate of 100 kHz over 5002 points. For a single source position, the wavefield was thus recorded as a "seismogram" representing the vertical component of the particle motion velocity at the surface of the granular medium. For each acquisition, TDR data were also recorded with a probe implanted between the acquisition profile and one of the tanks.

3. Model characterisation

The seismograms presented in Fig. 2 were obtained with the dry model (PM1-D, Fig. 2a) and with two distinct depths of capillary fringe (z_{cap}), estimated visually through the glass walls of the aquarium (PM1-W1 with z_{cap} = 100 mm, Fig. 2b; PM1-W2 with z_{cap} = 50 mm, Fig. 2c). Despite possible multiples due to ringing of the stick (Sr), each seismogram presents similar and coherent wavefields in which both P- and P-SV wave trains clearly appear. Bottom reflections (rP) are clearly identified as well on PM1-D and PM1-W1 models. Energetic events with very low frequencies and low apparent velocities (C) are also visible at different times, masking part of the signal contained in the P-SV wave train. These events are probably originating from the conversion of guided waves at the interface between the granular medium and the glass walls of the aquarium. Seismograms obtained with different water levels present a clear increase of the attenuation compared to the seismogram obtained with the dry model.

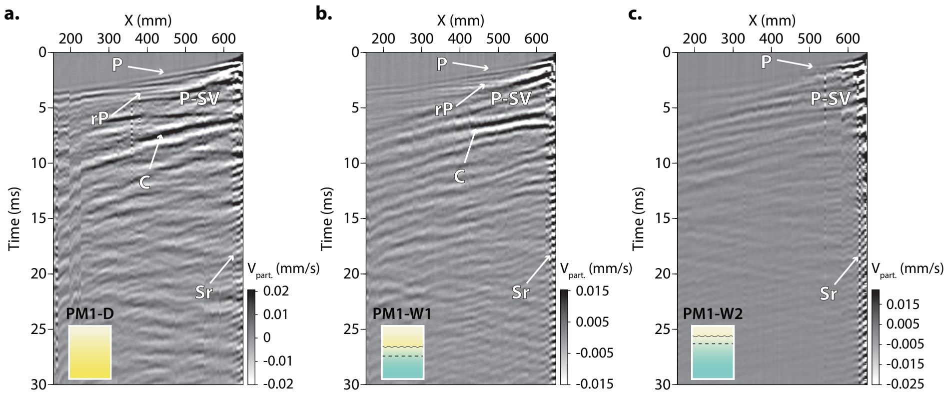

Fig. 2. Seismogram of particle velocity, vertical component, recorded on model PM1 with increasing water level: (a) dry model PM1-D, (b) wet model PM1-W1 with z_{cap} = 100 mm and (c) wet model PM1-W2 with z_{cap} = 50 mm.

As proposed by Bodet et al. (2010, 2014), the P and P-SV events identified on the seismograms can be interpreted as typical seismic events. Considering the P-wave train of weak dispersion at high frequencies, first-arrival times can be picked as pressure waves. As for P-SV events, the recorded wavefield can be transformed into the frequency-wavenumber domain where dispersion curves corresponding to the propagation of surface waves can be extracted. When studying dry unconsolidated granular material, traveltimes and dispersion data can finally be inverted (in the framework of ray theory and surface-wave theory respectively) to infer 1D velocity structures *versus* depth, assuming P- and S-wave propagation velocity ($V_{P,S}$) to be power-law dependent on pressure (Bodet et al., 2010, 2014).

The results show a decrease of first arrival times for the partially saturated models PM1-W1 and PM1-W2 compared to the dry model PM1-D (Fig. 3a). The non-linear increase of first arrival times with the offset related to the velocity gradient in depth remains visible for PM1-W1, while PM1-W2 shows first arrival times divided along three segments with distinct slopes. As for P-SV dispersion curves, both fundamental and first higher modes show an overall trend of increasing phase velocities for PM1-W1 and PM1-W2 relative to PM1-D (Fig. 3b). For frequencies above 0.75 kHz, propagation modes observed for the wet models are nearly coincident. At lower frequencies, the fundamental modes oberved for both wet models are characterised by an increase of phase velocity followed by a decrease, with slightly shifted maxima. Furthermore, TDR results are fully consistent with the rise of the water level in the medium, showing the appearance of a negative amplitude step with increasing width, followed at longer times by a plateau of positive amplitude decreasing with the rise of the water level (Fig. 3c).

4. Conclusions

Laser-Doppler experiments were performed here in order to monitor granular media with varying water levels in the context of both hydrogeological and seismic analogue modelling. Preliminary results clearly show the influence of increasing water level on the recorded wavefield. If the first arrival times seem to systematically decrease with the rise of the water level (indicating an increase of V_P), the behavior of dispersion data is more variable. Indeed, the results obtained on both wet models suggest the presence of lower V_S in depth relative to the dry model, and slightly higher V_S in the surface. Before pursuing further the interpretation of first arrival times and dispersion data to retrieve V_P and V_S structures, it seems essential to develop an inverse approach to estimate the saturation profile of each model from TDR data using 1D multi-layer models with varying water content. More generally, the experimental set-up proposed here validates the use of seismic wave propagation physical modelling to benchmark, at the laboratory scale, recently developed methods for water saturation detection in hydrogeophysics.

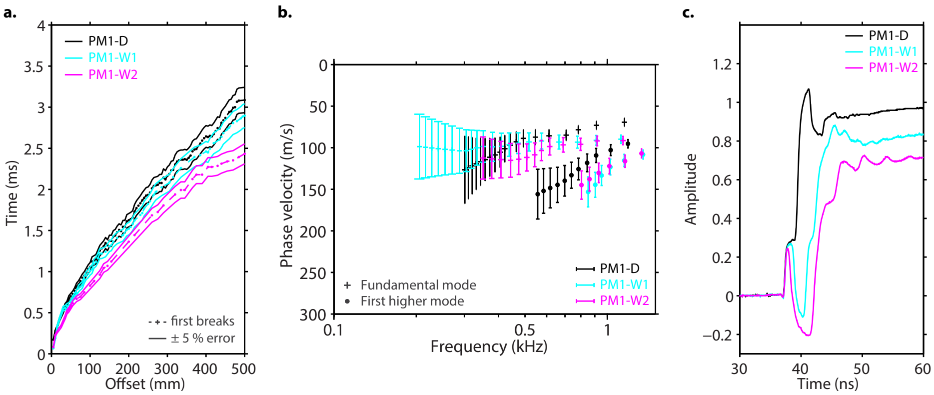

Fig. 3. (a) P-wave first arrivals picked for the dry model PM1-D (black), and the wet models PM1-W1 (cyan) and PM1-W2 (magenta). (b) Dispersion curves of the identified P-SV propagation modes for each model. (c) TDR data recorded for the different water levels.

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