Journal of Applied Geophysics 74 (2011) 81–88

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Elastic-wave identification and extraction through array processing: An experimental investigation at the laboratory scale

Benoit De Cacqueray [a,b,*], Philippe Roux [b], Michel Campillo [b], Stefan Catheline [b], Pierre Boue [b]

[a] CGGVeritas, Massy, France. 1, rue Léon Migaux, 91341 Massy Cedex, France
[b] ISTerre, CNRS UMR 5275, Université Joseph Fourier, BP 53, 38041 Grenoble Cedex 9, France

ARTICLE INFO

Article history:
Received 14 February 2011
Accepted 14 April 2011
Available online 22 April 2011

Keywords:
Surface waves
Wave separation
Beamforming
Laboratory-scale experiment
Agar-agar
Elastic wave
Array processing
Geophysical exploration

ABSTRACT

The mix of body waves and surface waves is a recurrent problem for deep exploration in geophysical contexts. As surface waves represent up to 70% of the recorded energy, they hide a large part of the information coming from the sub-surface through body waves. Efforts have been made in the past to better filter or remove surface waves; however, their impact is always far from negligible, especially with strong backscattering contributions. In parallel, taking advantage of an always growing number of channels, geophysical explorations face new opportunities to enhance the quality of Earth imaging. For example, better spatial sampling is a way to better use or remove surface waves. There are compromises to find between higher spatial sampling and operational costs, even for on-field tests. In this context, surface-wave studies at the laboratory scale are a flexible way to evaluate new acquisition designs and processing. This study shows how a gel-based phantom can be used successfully to study elastic-wave mixing in the context of geophysics prospection. Small-scale experiments provide the records of thousands of traces. Using projections in the slowness/angle domain, wave separation and identification algorithms are proposed, with the goal of being able to adapt array processing to geophysical-like designs.

1. Introduction

The issues associated with the mixing of body waves and surface waves have been known since the beginning of exploration geophysics. Surface waves are very energetic, and they represent up to 70% of the energy recorded with sources and receivers at the Earth surface. They represent a recurrent problem for deep exploration, as they can hide a large part of the information coming from the Earth subsurface through body waves. Thus, filtering and/or modeling surface waves to cancel their impact are a constant subject of research. This takes on ever more complex simulations and tests, in particular due to the massive number of channels. Multi-component technologies, and high-density and large-area acquisition lead to simultaneous records of several tens of thousands of channels. In this context, a simple on-field test represents months of work for many people. On the other hand, simulation does not take into account all of the complexity of the field conditions. To investigate some situations, experimentation in the laboratory environment is often an attractive alternative.

Using a gel-based phantom to study wave propagation at the laboratory scale is not new. In 1927, experiments described by (Terada and Tsuboi, 1927) demonstrated the presence of Rayleigh waves in an agar-agar phantom. In medical ultrasonics, gels are widely used as *in-vitro* phantoms, to mimic human tissue. In wave physics, a lot of laboratory experiments have been carried out to study wave propagation in complex media (Fink et al., 2000). In the geophysics context, Bodet et al. (2005), Bretaudeau et al. (2008) and Campman et al. (2005) used experimental results in their studies of surface waves. On the other hand, laboratory configurations mimicking elastic-wave propagation with large amounts of data and deeper exploration (like in geophysical contexts) have seen little investigation. The main goal of this study is to realize high-density acquisition at the laboratory scale, and to investigate the correct design and/or processing to improve surface-wave and body-wave separation and identification.

In a gel with about 6% agar-agar, P-wave velocities are about 1500 m/s, and S-waves and Rayleigh waves, around 9–10 m/s. The speed ratio between P-waves and S-waves makes the P-waves nearly invisible below 1000 Hz, since their wavelength is much larger than the propagation medium. Working in gels below 1000 Hz then means dealing with shear and Rayleigh waves. With a velocity ratio of about 95%, this mix is a good approximation of the geophysical environment, where the surface-wave and body-wave velocities are similar.

Considering pulsed signals with a 500 Hz central frequency, the central wavelength is around 20 mm. With the size of an agar-agar block at 450 mm × 145 mm × 102 mm, enough distance is provided to observe wave propagation of several wavelengths between the source and receiver. The source is a circular 20-mm-diameter piezo-electric

* Corresponding author at: ISTerre, BP 53, 38041 Grenoble Cedex 9, France. Tel.: +33 4 76 63 52 43; fax: +33 4 76 63 52 52.
E-mail address: benoit.de.cacqueray@cggveritas.com (B. De Cacqueray).

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doi:10.1016/j.jappgeo.2011.04.005

transducer, and as a receiver, we use a laser vibrometer that records the time-domain vertical component of the wavefield velocity at the gel interface. The sampling frequency is 10 kHz. As illustrated in Fig. 1, we also use two remotely operated stepped motors to tilt a mirror in both directions, and thus to scan a 120 mm × 120 mm area of the gel surface with the laser vibrometer.

The two main advantages of using a laser vibrometer are: (1) to avoid any gel–sensor coupling issues; and (2) to allow very fine resolution at the gel surface. A possible drawback is the signal-to-noise ratio of the received signal. We use the Ometron VQ 500 laser-vibrometer with a full measurement range of 20 mm/s allowing a resolution of 0.02 $\mu m/s/\sqrt{Hz}$. The sampling frequency ranges from 0.5 Hz to 22 kHz. To enhance the signal quality, we emit a 3-s-duration linear chirp from the piezo source, ranging from 120 Hz to 850 Hz. After its propagation in the gel, the low-amplitude signal is received by the laser vibrometer and is cross-correlated with the emitted chirp, which leads to a 40 dB signal-to-noise ratio pulsed signal at any point of the gel surface. With a scale ratio of about 30, the 20-mm piezo size does not match the size of the vibrator trucks at the true scale. However, the objective of the laboratory-scale experiments is not to match the true-scale experimental configuration with high fidelity, but to reproduce, to some extent, the physics of wave propagation encountered during seismic exploration. In particular, the goal of this study is to deal at the laboratory scale with the ground-roll problem that appears when undesired surface waves mix with body waves. Surface waves appear as low-velocity, low-frequency, high-amplitude coherent noise that generally obscures the signal and degrades the overall data quality. Here, we show that the ground-roll problem can be alleviated through array-processing when the acquisition is performed between two arrays of sources and receivers.

This report is organized as followed: Section 2 describes the array-processing algorithm that is performed on both the source and the receiver arrays, moving from classical one-dimensional (1D) simple beamforming to the 2D double beamforming (DBF) used in this experimental configuration. Section 3 gives the advantages of the slowness representation, while Section 4 illustrates the wave-extraction abilities of DBF processing. In Section 5 the originality of the DBF extraction is discussed, before rounding things off in the conclusions in Section 6.

During this experiment, a total of 49 (sources) × 126 (receivers) = 6174 traces were recorded in the experimental configuration described in Fig. 2(a). The time-domain signals presented in Fig. 3 are a subset of the raw data after the correlation of the received signals with the emitted signal.

The wavefield is composed of a direct surface wave and several reflections, although the high number of mixed waves makes the interpretation very difficult. One way to describe these data is to split them in a 5-dimensional space $S(t, x_i, y_i, x_j, y_j)$, as we record signals as a function of time, receiver positions (defined in x_i and y_i), and sources positions (defined in x_j and y_j).

Sorting out the data space into a source-array/receiver-array space allows array processing techniques to be applied as a way to facilitate wave separation and, if possible, identification.

2. Double beamforming

Among the various array processing techniques, beamforming is widely used in multi-source and/or multi-receiver configurations. Array use started early in radio astronomy and nuclear detection, and

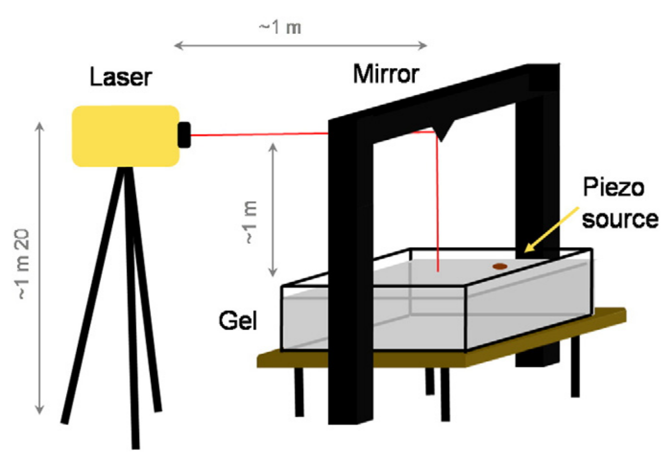

Fig. 1. Experimental configuration. The agar-agar gel is placed in a rectangular Plexiglas aquarium. The wavefield measurement is performed using a laser vibrometer pointing at the gel surface via a mirror mounted on an aluminum frame at about 1 m above the gel surface. Two high-precision motors are fixed on the mirror, to allow variable tilt for scanning of the gel surface. A circular 20-mm-diameter piezo-electric transducer fastened to the gel surface is used as a source. Pulsed signals with a frequency bandwidth ranging from 150 Hz to 850 Hz are emitted. The piezo source, the laser vibrometer, and the mirror are remotely operated by a computer.

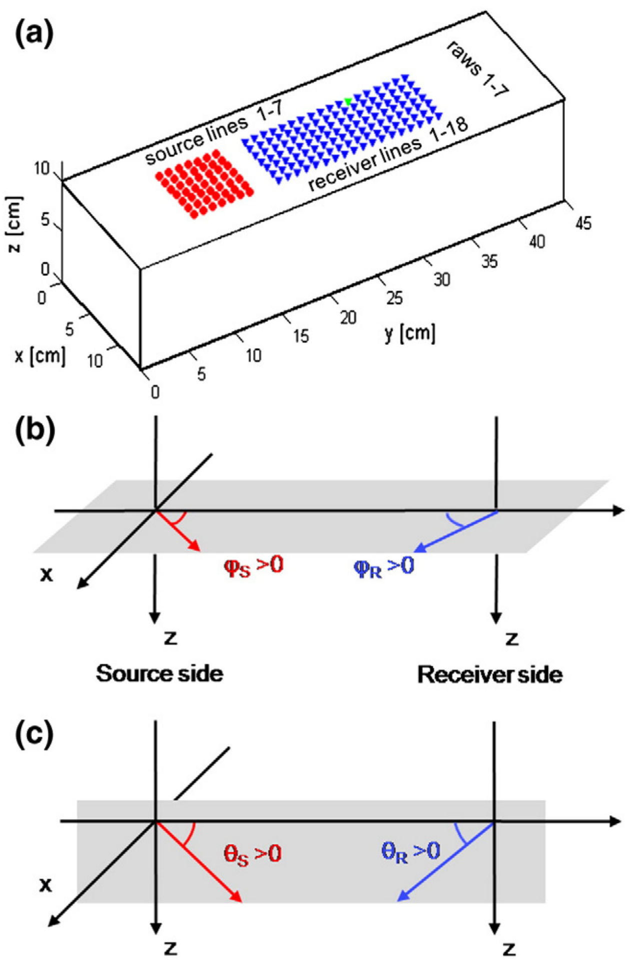

Fig. 2. Experimental design and angle definitions. (a) Experimental set-up implemented at the laboratory scale. Each red circle indicates a source point and each blue triangle a receiver point, corresponding to one piezoelectric source and one vibrometer spot, respectively. The sources and receivers are positioned on lines and rows spaced by 10 mm, for one source antenna of 7 × 7 sources (red) and 18 lines of 7 receiver points (blue). On the receiver side, a sub-antenna is defined by a square of 7 × 7 receivers. We can then consider 12 receiver sub-antennas with sub-antenna 1 as lines 1 to 7, sub-antenna 2 as lines 2 to 8, *etc*. Receiver 78 corresponds to the first of the 12th line of receivers and is highlighted in green (see Fig. 3) (b) Source and receiver azimuth angles (φ_s, φ_r). For symmetry reasons, the azimuth for the sources is taken in an inverse trigonometric sense. (c) Source and receiver incidence angles (θ_s, θ_r) with the same convention. For easier understanding of the results in Section 3, the incidence angle is defined as complementary to the classical one.