Quantitative imaging using Surface acoustic waves

by

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Abstract

Most of acoustic imaging systems make use of P waves for building up images. Those systems are highly blurred with the interface echoes when sub-interface imaging is concerned. Surface waves are generated and propagate on the interface. Their energy is guided on a layer of about a wavelength below and above the interface. They can thus be used as a carrier of information from below to above the interface. Two types of waves are described in this paper: Stoneley-Scholte Waves (SSW, marine environment) and Rayleigh Waves (RW, land environment). Their properties will be investigated in details, in particular reflexion and refraction of these waves and velocity dispersion. Inversion procedure using SSW waves will be presented and applied to scaled tank experiments. Refraction and reflection of SSW waves will also be studied experimentally.
Taking into account the results of theses investigations tomography algorithms as well as sector-scan imaging will be investigated on mock-ups.
Several applications will be presented on real scale: estimation of marine sediment properties using SSW, detection of caves using RW and detection of land mines using RW. For each case, experimental set up will be described and results are shown.

Key words: Stoneley-Scholte waves, Rayleigh waves, velocity dispersion, inversion, tomography.

Surface waves imaging

Introduction

Most of imaging systems used P waves as a carrier of information. They are seriously blurred by interface echo when sub-bottom imaging and characterisation is concerned. The surface acoustic waves are guided on the interface [1] and offer the advantage of using the interface as a carrier of information (and not as a spurious echo).

Properties of surface waves

- They are guided on the water-sediment interface and possess a cylindrical spreading geometry (instead of spherical for p or S wave sources), less transmission loss
- They are evanescent:
  - Polarized
  - Exponential vertical amplitude decrease
- Their velocity is directly related to shear waves velocity
- Their penetration depth depends on the frequency (about one wavelength). For a varying velocity profile, each frequency carries information on a corresponding depth
- Group velocity dispersion depends on the velocity profile in the sediment.

The penetration properties for marine applications are shown in table 1.

PROPERTIES	**BOTTOM TYPE**	
	soft bottom $c_{ss} < c_w$	**hard bottom** $c_{ss} > c_w$
Energy concentration	in the sediment	in the water
penetration depth	λ in the sediment λ in the water	λ in the sediment several λ in the water
velocity	dispersion equation $\approx 0.8\ c_{ss}$	dispersion equation no approximation

Table 1: Properties of surface waves in the case of marine sediment
c_{ss} shear wave velocity in sediment, c_w: wave velocity in water

Velocity dispersion of Stoneley-Scholte waves

In order to mock up real sediment, a material has been built whose properties vary continuously with thickness (z: depth in mm, error: ±20 m/s) [3]:

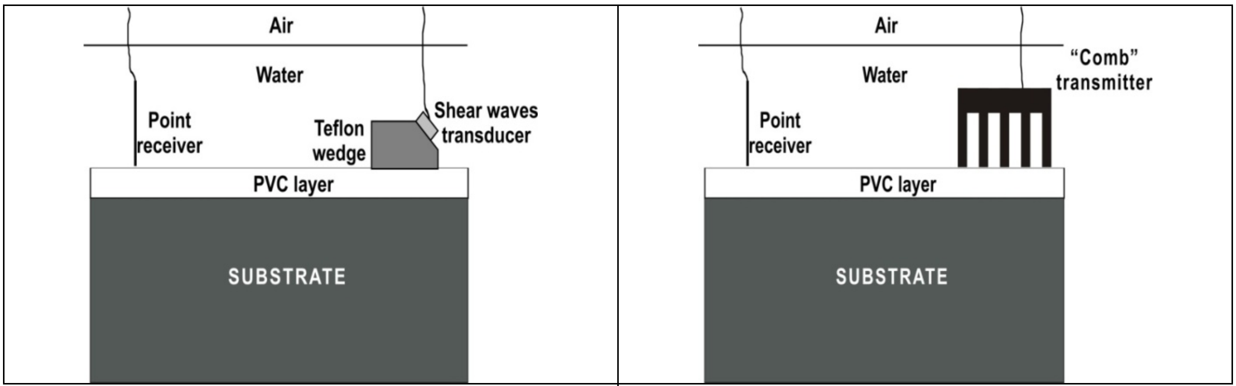
- Thickness: 1cm
- $C_l = 107.z + 2030$ [3100 - 2030 m/s]; $C_t = 24.z + 830$ [1070 - 830 m/s]

For such a material, the velocity dispersion can be computed theoretically and compared to experimental data (scaled tank experiment).

As the velocity of SSW is lower than S-waves velocity, such evanescent waves cannot be generated by a plane incident wave (negative angle required). Two set ups have been used that are shown in figures 1:

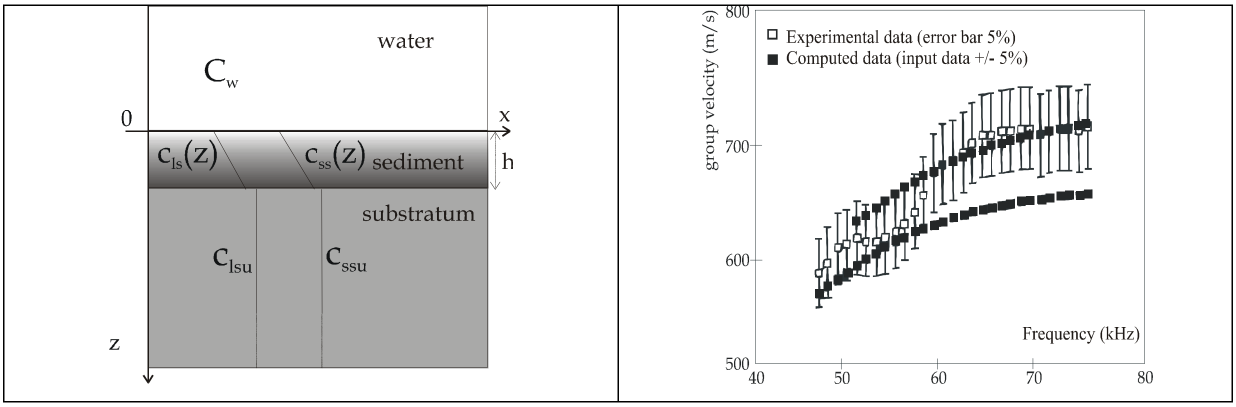
a. Shear waves wedge
b. Periodic (comb) excitation).

Surface waves were recorded thanks to a point receiver near the interface. Wigner-Ville time-frequency analysis [2], [24] was achieved to characterize the dispersion and to estimate velocity dispersion by estimating group delay for two positions.



a-shear wedge | b-periodic (comb) excitation

Figure 1: Generation of SSW in a tank (mock-up experiments)



a-Experiment geometry | b-Results

Figure 2: Velocity dispersion of Stoneley waves

Results displayed in figure 2b show that the velocity dispersion values fit the theoretical ones within a range of ±5%. 5% is the order of magnitude of the error on the measurement of the velocity profiles on thin layers of 1mm. These values have been used to feed the prediction of velocity dispersion (direct problem solving).

Inverse problem

Inverse problem consists in estimating the velocity profile in the sediment from the velocity dispersion of SSW. An innovative method has been developed that is based on the use of Artificial Neural Network, ANN, [3], [4], [5], [6], [15], and [19]. Inversion is achieved in two steps:

- train the network with values of velocity dispersions for several set-ups and
- ask the networks to guess the set-up from dispersion data.

The first case investigated was a simulation study of SSW propagating a homogenous layer of sediment over an infinite substratum. A total of 625 realisations of the direct problem were computed. Half of the computed values (randomly chosen) were used to train an Artificial Neural Network, and the other half for testing the inversion performance.

The range for every characteristic parameter was rather wide as shown in table 2. The results of the inversion are shown in table 3.

	Thickness m	**c_t m/s**	**c_l km/s**	**ρ T/m³**
Sediment	$3<h<19$	$140<c_t<460$	$1.7<c_l<2.9$	$1.4<r<2.2$
Substratum	Semi-∞	3.85	6.3	2.7

Table 2: range of values for simulating the direct problem
(5 values were picked up for every characteristic parameter).

Parameter	**e**	**c_t**	**c_l**	**ρ**
Errors ε	5%	2%	18%	17%

Table 3: inversion errors on simulated data

It is well known that SSW velocity is highly related to shear wave velocity and thickness while it is less sensitive to p waves velocity and density. This explains why the errors in table 3 are less for highly sensitive parameters. The shear velocity is related to shear strength and is of high interest when geotechnical properties of sediment are under investigation.

The second case investigated consists in training the ANN on simulation result and achieve the inversion on experimental data. Both a constant velocity layer and a linear velocity profiles layer were studied.

Table 4 show the inversion error for a constant velocity layer: 1 layer of polypropylene over an infinite substrate (e=10 mm, c_s=920 m/s, c_l=2222 m/s, ρ= 969 kg/m^3).

Parameter	**m**	$\mathbf{c_t}$	$\mathbf{c_l}$	**r**
Errors ε	11%	<0.5%	≅20%	≅20%

Table 4: inversion errors on experimental data

For the continuously varying layer, only a few couples of velocity dispersion were used (c, f) (7 bins/octave) with poor *a priori* information: variation range of parameters: 1.6 to 6.
5 realizations of the direct problem were computed for each parameter: Thickness, Cl profile (2 parameters), Ct profile (2 parameters). Thus the direct problem was solved for 625 cases. Inversion performances using experimental data (described in figure 2) were also very accurate:

- shear velocity: ε < 0.5%
- thickness: ε < 11%
- other: ε < 20%

Refraction and reflexion of Stoneley-Scholte Waves, SSW [12], [14]

Even for simple cases, the reflection and reflection conditions of SSW are not easy to predict theoretically. Some papers assume the continuity of each component of the evanescent waves, some other the continuity of the resulting component. In a 3D case (or in the presence of a complex obstacle) the problem is too complex to be predicted theoretically. In order to investigate the SSW in our range of interest (marine sediments), we have had a heuristic experimental approach and studied many cases and geometries. From many experiments, the conclusion was that SSW traveling follow laws similar to Snell-Descartes ones as described in figure 3:

- SSW is reflected as a SSW (with same velocity)
- SSW is transmitted as another SSW (with a SSW velocity corresponding to the second medium)
- A critical angle was observed (similar to the one encountered for compression waves)
- No other waves or components could be observed in any experiment (< 40 to 60 dB)

Although the behaviour of SSW can be very complex for a complex scenario (i.e. for an embedded shell, one can encounter the conversion of a SSW evanescent wave into SSW but also into Lamb waves, for instance), the heuristic investigation confirms that **SSW can be**

used as any conventional wave for either imaging or tomographic reconstruction as we will see in the following sections.

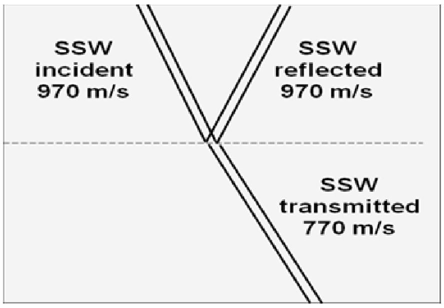
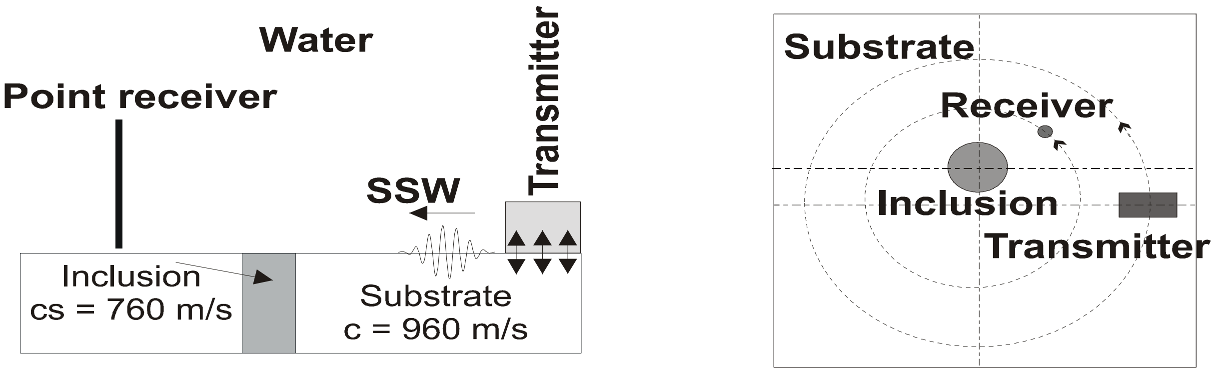


Figure 3: Reflection and refraction of SSW

Tomographic reconstruction [13], [14], [18]

Tomographic reconstruction consist in using SSW to reconstruct shear velocity profile in the substrate as shown in figure 4: both transmitter and receiver can rotate around the area of interest (shear wave velocity change of about 25% in this experiment). The rotation of transducers is not centred on the centre of the inclusion in order to avoid any artefact in the reconstruction (i.e. the complex geometry has been studied and not the simple one). All signals are stored and then processed using conventional tomographic algorithms [13], [14], [14], [18].



Figures 4: Tomography experiment

A typical tomographic reconstruction result is shown in figure 5 where geometrical shape (circle) has been properly reconstructed.

From a quantitative point of view, the performances depend on the reconstruction method used

- best estimation of medium properties by back-propagation method:
  - RMS error < 1 m/s (0.1 %), bias < 14 m/s (1.4 %)
- best estimation for inclusion by Simultaneous Iterative Reconstruction Technique:
  - RMS error < 26 m/s (3.4 %), bias < 36 m/s (4.7 %).

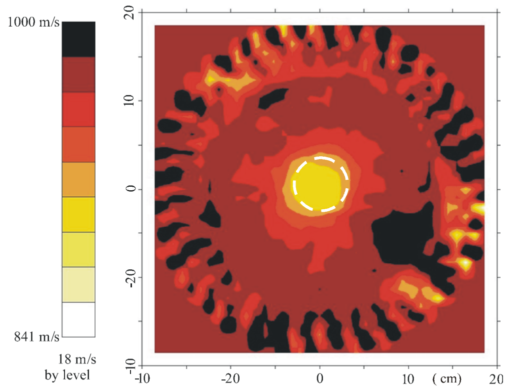


Figure 5: Results of tomography reconstruction of a cylindrical inclusion in the substrate

Surface wave sonar

Considering their refraction and reflexion properties SSW can be used as any other wave for sonar beamforming for object detection. Two types of experiments have been run:

1. Investigation of the Energy distribution around and object, Maps of the Energy near the interface, MoE, for understanding the scattering phenomena.
2. Conventional sonar processing and beamforming.

Tank experiments with embedded objects [7], [9]

The mock-up used for tank experiment is described in figure 6. Several objects from various shapes and sizes were embedded at various depths in a uniform substrate. A SSW is used and a single receiver is scanning the surface, either in a uniform rectangular grip (MoE) or on a linear path to simulate a sonar receiving array.

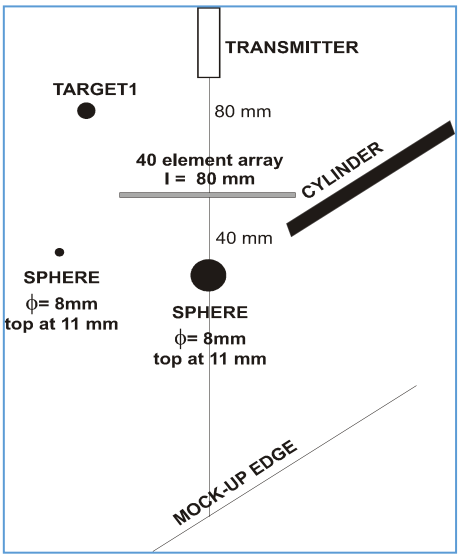
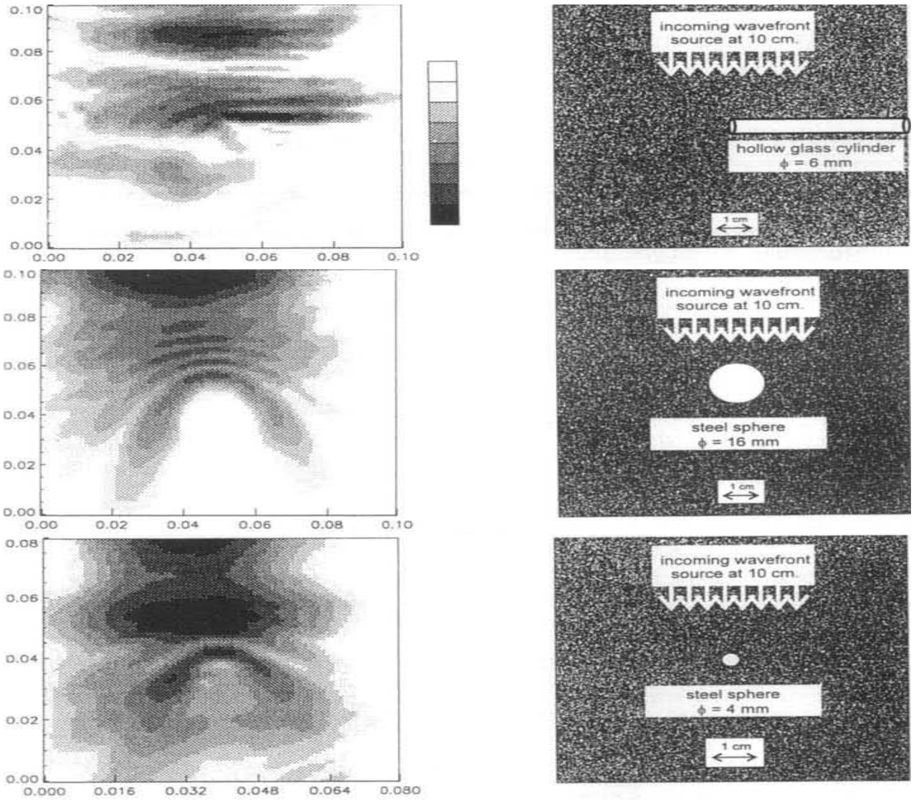


Figure 6: Detection of embedded objects, scaled tank experiment

Energy maps on the interface are shown for several targets in figures 7. For all these figures, the central frequency is 100 kHz and the scanned area is 10x10 centimetres.



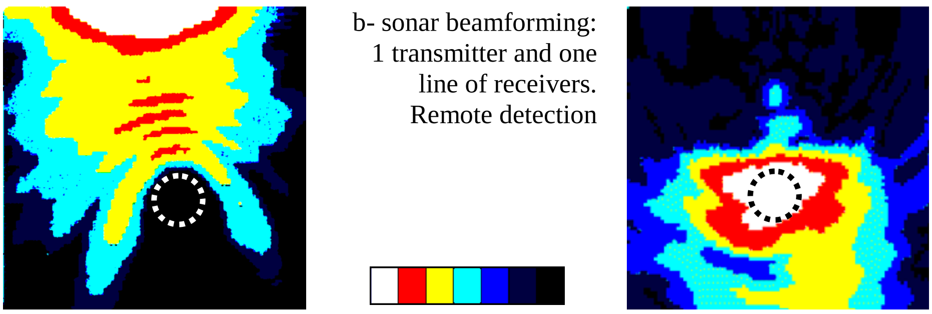
Figures 7: SSW Energy maps for various objects (3dB/grey level).

These figures clearly show the scattering of SSW around the embedded objects even in the case of a small target (0.5 λ). This effect reminds the shadow effect in sidescan sonar images.

SSW sonar system

As shown in figure 7, conventional sector sonar geometry has been investigated with one wide aperture transmitter and a line array of receivers for beamforming [8]. Velocity of SSW was first estimated experimentally then used in a conventional beamforming algorithm. The detection performance is clearly shown on figure 9b. This figure is to be compared to figure 9a (energy distribution).

a-MoE/
full scan
of the surface (10x10
cm)



b- sonar beamforming:
1 transmitter and one
line of receivers.
Remote detection

Figures 8: Detection of an embedded sphere (scale: 10 x 10 cm, 3db/colour).

Field experiments: Application to landline detection and classification (RW) [21], [22]

The sector scan method (one transmitter and one line of receivers) has also been applied in the airborne case for the detection of buried land mines. The beamforming result is to be compared with figure 8b. the only difference is that for fig 8B data is displayed in Cartesian coordinates (to compare to MoE) while, for figure 9, they are displayed in polar coordinates.

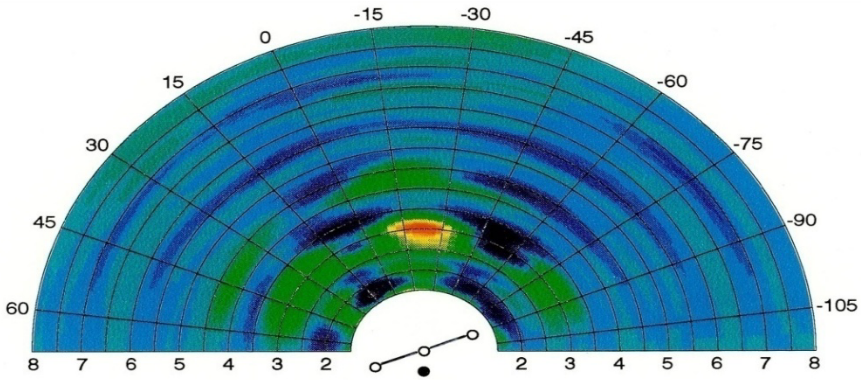
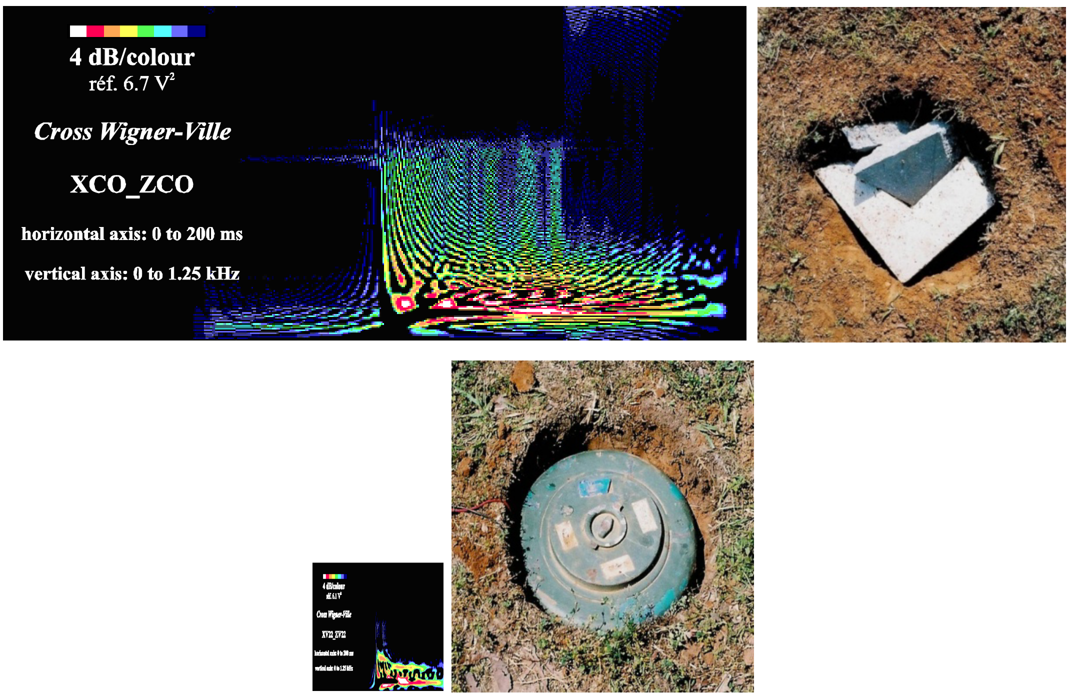


Figure 9: Sector scan sonar using RW, Detection of a land mine.

In addition to the detection of landmine, an attempt of classification between a mine and a rock-type target was achieved using the two components of Rayleigh waves associated to instantaneous cross-spectrum processing (cross Wigner-Ville [24]).



Figures 10: Cross Winger-Ville Analysis of RW components.

Both experiments and theoretical investigation on SSW and RW have shown the potential of these surface waves for quantitative imaging sub-interface either for sediment characterisation of for the detection (and classification) of embedded objects . We will now investigate their application in the seismic areas in both marine and land domains.

Application to sediment characterization at sea (SSW)

A typical sea experiment is sketched in figure11that also illustrates the variation of depth penetration of SSW with frequency. Transducers used are an airgun for transmission and a streamer of hydrophones (24 at 5 m spacing). The equipment was installed on a dedicated geophysical vessel. The site comprised a thick sequence of normally consolidated to lightly overconsolidated clays. Airgun generates spherical waves that are converted to SSW. Surface waves can be discriminated from p waves by their late arrival.

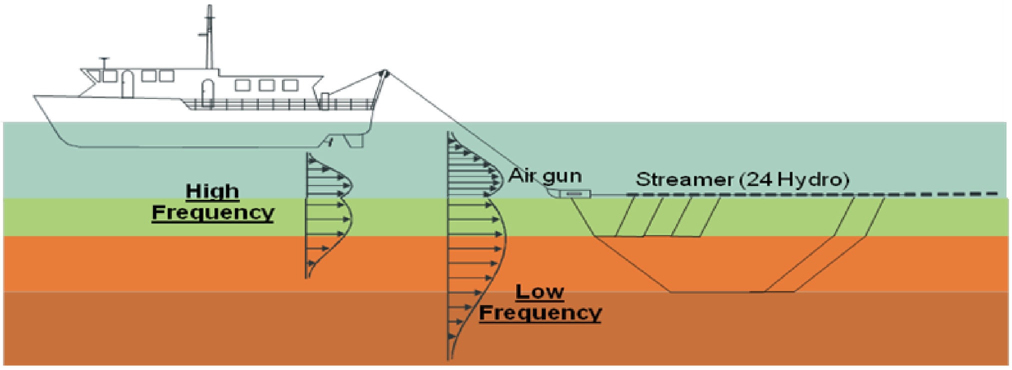
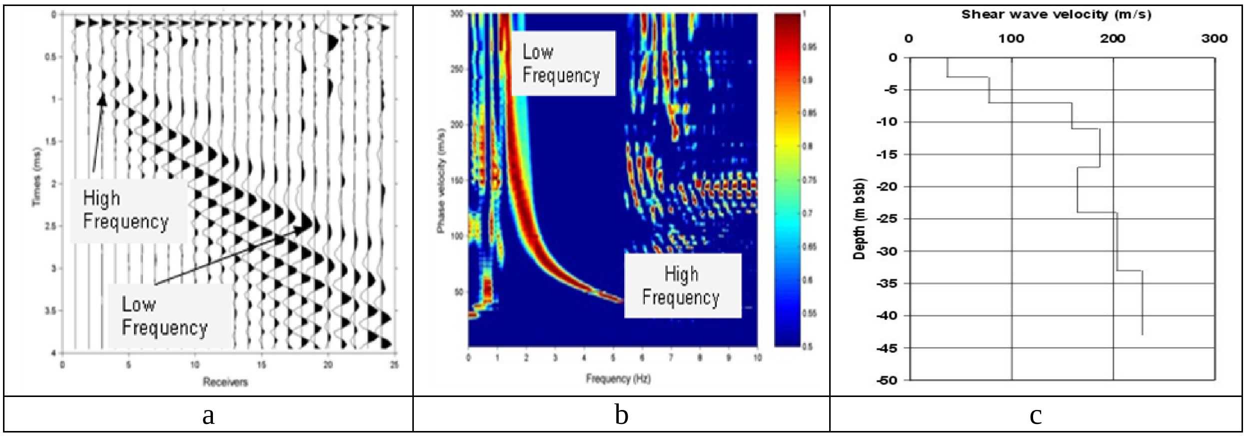


Figure 11: Sketch of sea experiment

The seismic system was towed at a speed of about 2 knots. Airgun shots were made at 20 to 50 m intervals. First data quality check was achieved onboard.

Figure 12a shows an example of received signals for one transmission at a given spot. Processing raw signals can lead to velocity dispersion curves (fig 12b). The coupling of velocity dispersion with a numerical model (multilayered sediment) is then used to estimate velocity profile associated to the spot (fig 14c).



Figures 12: Examples of raw signals and processing outputs

a- Signals received for each transmission,

b- Velocity dispersion curves, c- Corresponding velocity profile.

Ground truth was obtained by comparing estimated shear waves profile to a profile obtained with a conventional cone penetration test CPT: a cone equipped with a 3-axis accelerometer is pushed into the soil to the required depth. A shear wave is generated at the seabed by striking a hammer on a frame resting on the seabed, and the wave arrival is recorded. Subsequently, the cone is advanced and the test repeated. The ratio between test depth and delay gives the average shear wave velocity in the depth interval. The comparison of estimated values (using SSW) to ground truth (using CPT) is given in figure 13. Error is of the order of 10 to 20% mainly due to the fact that CPT method is a point measurement, while the acoustic measurements are integrated on an area of several square meters.

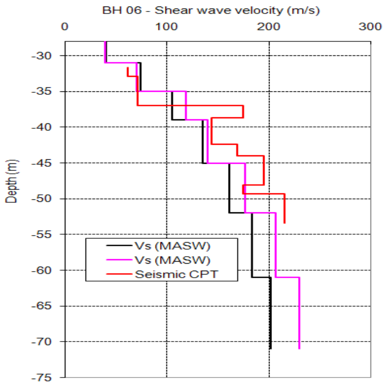


Figure 13: comparison of estimated values using SSW (MASW) to ground truth using CPT.

Continuous measurement and combining the SSW data to conventional seismic data (refraction seismic) lead to a large scale description (several km) of the sediment with **both acoustical** and geotechnical information as shown in figure 14. Colours in figure 14 correspond to velocities range and qualitative description of the sediment structure (table 5).

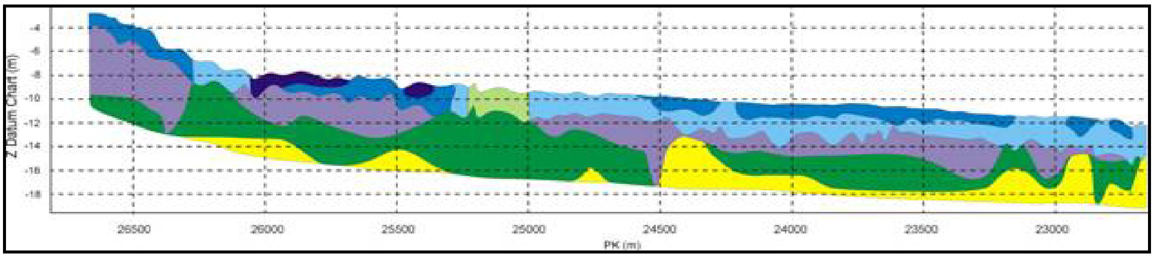


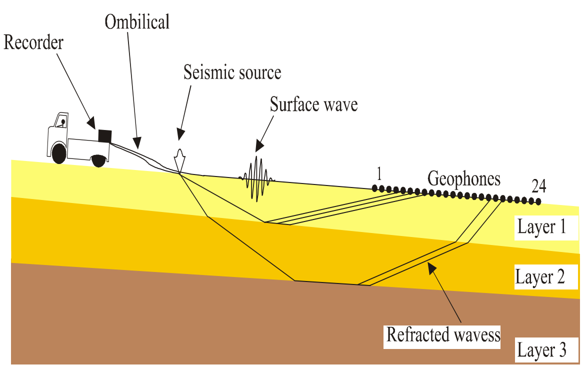
Figure 14: combining conventional seismic and SSW information for large scale description of sub-bottom structures

Units	P wave velocity (m/s)	S wave velocity (m/s)	Description (assumption)
#1	1500 – 1600	< 80	Recent deposit – silt, sand
#2	1500 – 1600	80 – 140	Recent deposit – sand and gravel
#3	1500 – 1600	140 – 220	Recent deposit – sand and gravel
#4	1500 – 1600	220 – 330	Outcrop of weathered moraine
#5	1800 – 2100	180 – 220	Weathered moraine
#6	1800 – 2100	220 – 330	Weathered moraine
#7	> 2100	>330	Lightly weathered moraine

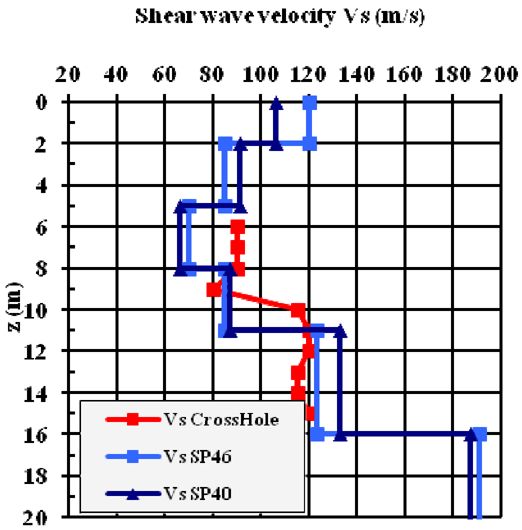
Table 5: qualitative and quantitative interpretation of colour scales of figure 14.

Application to cavity detection in land (Rayleigh waves)

The same inversion approach using SSW in marine applications has been applied using RW in land applications. The transmitter can be drop of a mass, a gunshot, explosives, or a shaker. The receivers are geophones (72) with variable spacing leading to a total array length of 71 to 213 m length The geometry of the land experiment is given in figure 15a while the output data is given in figure 15b (blue lines) for point measurements. For this application, ground truth was obtained by cross-hole measurements (red line). Once again the error is less than 10%.



a-geometry of data acquisition



b-estimated shear velocity profile

Figures 15: Use of Rayleigh waves for soil characterisation.

By towing the system, a map of the shear velocity in the area was reconstructed (figure 16) showing shear wave velocity as a function of range and depth.

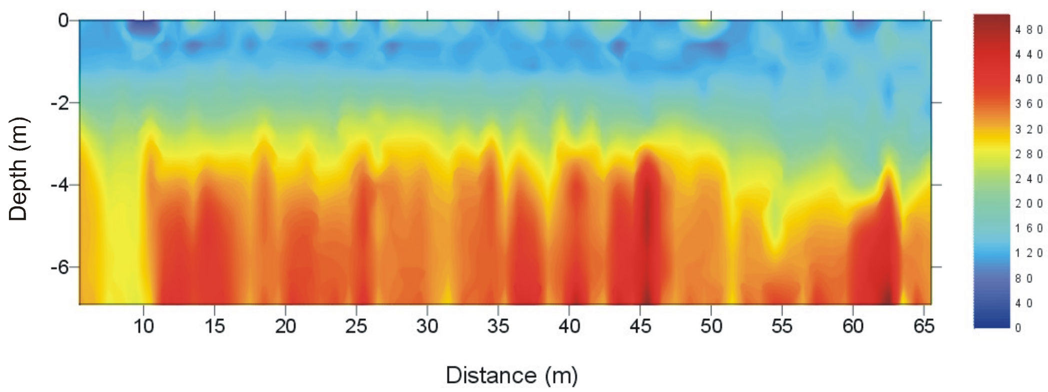
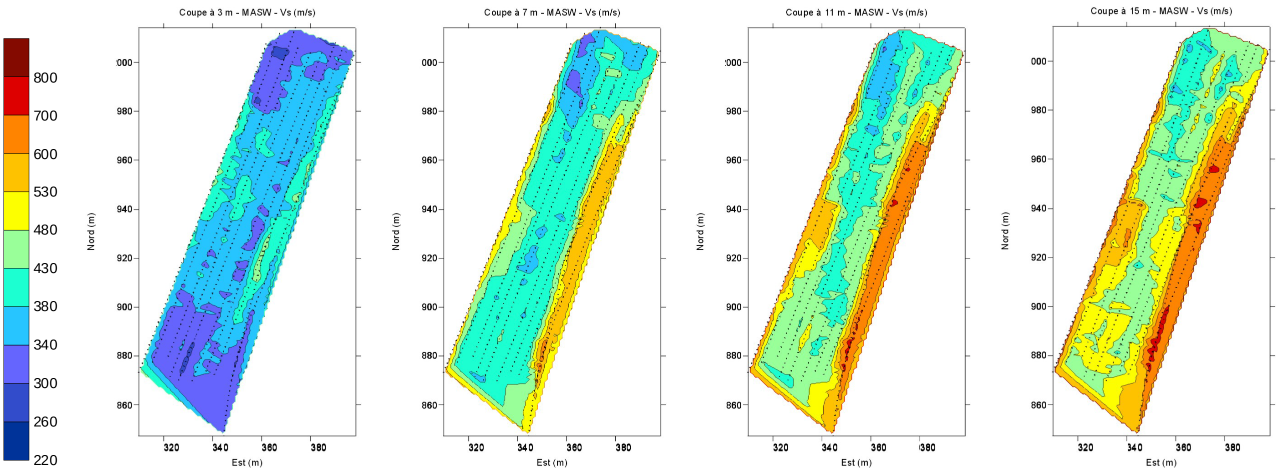


Figure 16: 2D map of shear velocity using RW

Area survey was achieved using multiple line acquisition. After processing and inversion data were represented in multiple layers representation for a better interpretation (figure 19).



Z ≈ 3 m Z ≈ 7 m Z ≈ 11 m Z ≈ 15 m

Figures 17: Area survey, 2D cartography of shear waves for every depth

Detection and localisation of underground cavities using RW

The last example of application is the use of RW for detecting and localising underground cavities. Such an application is of paramount importance in civil engineering as these cavities (voids, karsts, breaks of pipes ...) can cause great hazards for constructions. By using RW for prior detection, coring can only be achieved in suspicious areas. This will reduce considerably both cost and duration of land surveys.

An innovative passive method using RW was developed and patented by Sismocean: DCOS.

The DCOS method is based on a statistical analysis of the energy distribution of RW. It does use any assumptions about the ground geology, does not need any source and does not require any numerical model inversion.

The principle of the method is illustrated in figure 18: the spatial structure of both seismic ambient noise and anthropogenic one (traffic, industries …) are disturbed by the presence of a cavity underground. The presence of a cavity will disturb the field of all waves, in particular RW that carries information on underground velocity at various depths. The receiving array is divided into sub-arrays. When there is no cavity, both sub-arrays will receive the same energy the presence of underground inhomogeneities will modify the energy distribution.

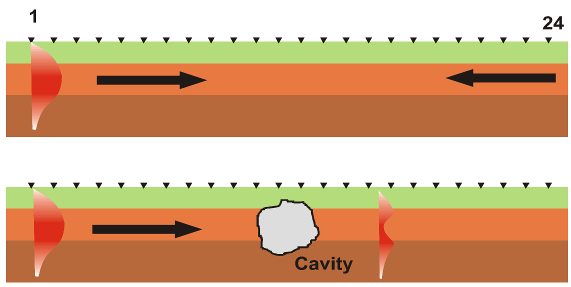


Figure 18: DCOS method
Energy distribution on sub-arrays is modified by the presence of an underground anomaly

Figure 19 shows an example of raw data. Data structure is very different than the one obtained in active seismic exploration (fig 12a).

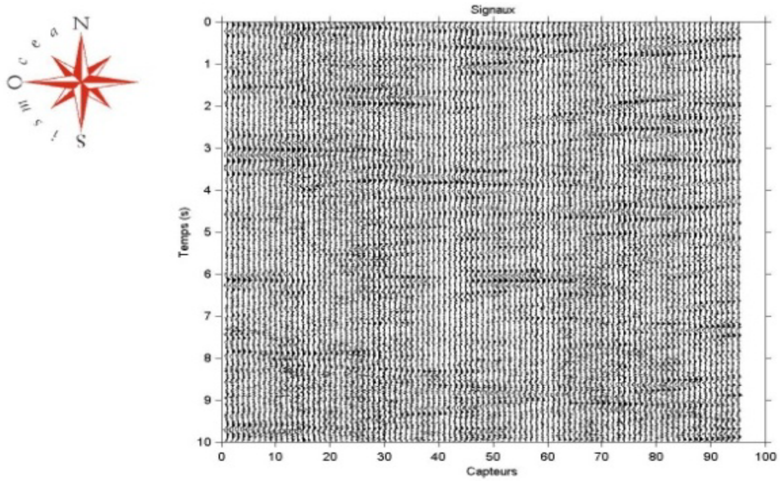


Figure 19: Example of raw data, passive RW.

Figure 20 show an example of DCOS detection of underground anomalies in a know area where two man-made cavities were present and well positioned. Man-made cavities positions are superposed. The correlation between the DCOS anomalies and the presence of cavities is clearly shown.

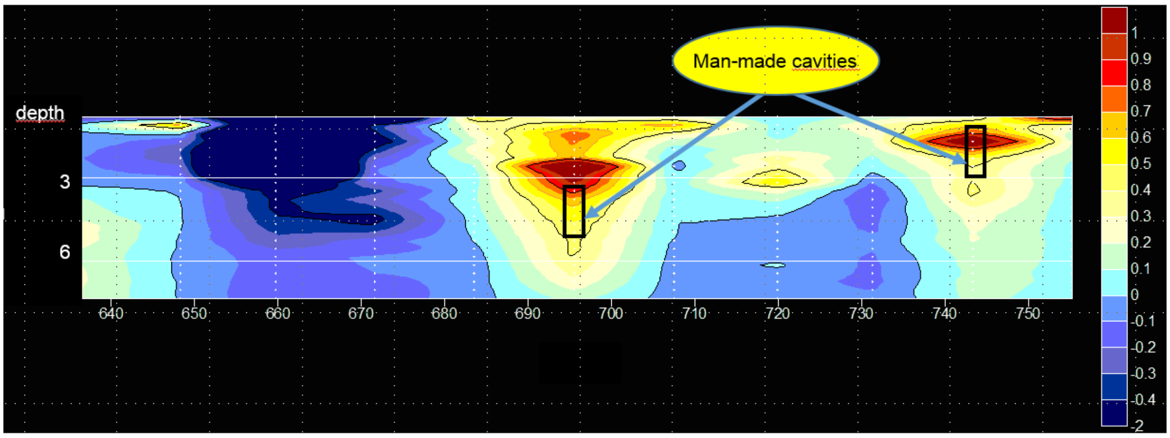
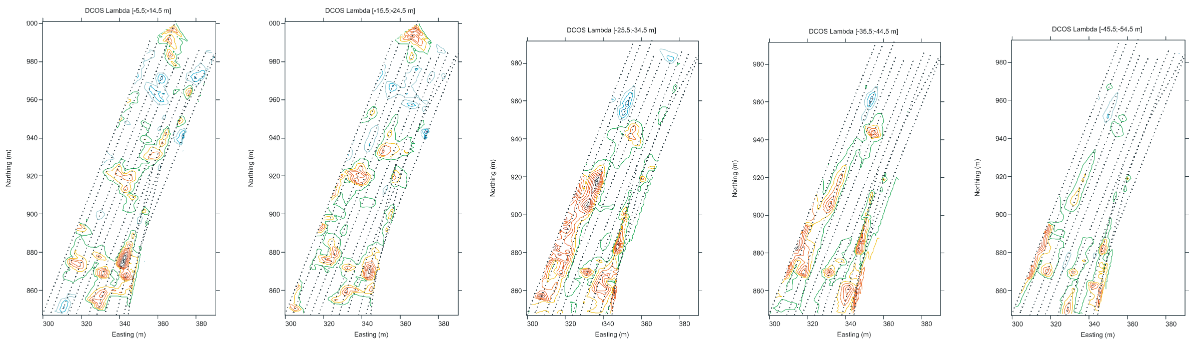


Figure 20: DCOS, Shallow investigation of man-made cavities

As in figure 17, when 2D DCOS scan is achieved one can represent the anomaly maps in 3D (for various depth) as shown in figure 21. For this figure, streamers were positioned every 2 meters. Inmost of the experiments, penetration depth was about 20 meters.



Z ≈ 3 m Z ≈ 6.5 m Z ≈ 10 m Z ≈ 13 m Z ≈ 16.5 m

Figures 21: 3D representation of DCOS anomalies (for every depth)

DCOS analysis:

Conclusion

IN this paper, we have investigated the properties of surface waves. Both Stoneley-Scholte Waves (SSW) and Rayleigh Waves (RW) were studied in details. Thanks to their propagation properties (penetration, reflexion, refraction) they were used in order to investigate the medium below the interface remotely. Several tank experiments have shown the potential of these waves (tomography, beamforming). Applications to real cases were presented: land mine detection and classification (RW), marine sediment characterisation (SSW) and underground cavity detection (RW). Both active and passive sonar concepts were applied to these waves successfully. Comparison to ground truth has pointed out very satisfactory performances of under interface quantitative imaging.

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