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Combination of Seismic Refraction and Marine Surface Wave to Characterize Near Surface Marine Sediments

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SUMMARY

Nearshore surveys are scheduled to acquire soil data to design pipeline landfalls, pipeline routes in shallow waters, jetties and breakwaters, loading / unloading facilities for LNG (Liquefied Natural Gas) and oil terminals, and other coastal developments. The combination of the seismic refraction and the underwater multichannel surface wave [U-MASW] is a very efficient quantitative geophysical tool to investigate the upper part of the seabed. It is a complementary method to standard geophysical tools such as multi-beam echo-sounders, side-scan sonar and sub-bottom profilers, which provide qualitative information. Refraction and U-MASW data are collected using a bottom-towed acoustic source and a low frequency hydrophone streamer. The U-MASW data processing is briefly described in this paper. The U-MASW output is a number of continuous shear wave [Vs] depth profiles covering the surveyed area. This paper presents the refraction and U-MASW results acquired along a pipeline route then the combination of both the analyses to propose a geophysical soil description. Combination of refraction and U-MASW is perfectly well adapted to investigate or localize areas where soil conditions are the most favorable for burial purposes. In addition, it is useful in order to define borehole locations and optimize the geotechnical program over the surveyed area.

Introduction

In the near-shore approaches, if the marine seismic refraction acquisition using a bottom towed source is quite common for pipeline route surveys, its combination with the marine surface wave is rarer. In Argentina, 100 km of marine refraction and surface wave have been simultaneous acquired, processed and interpreted in order to produce a continuous profile showing P wave velocity and stiffness variation of soil below sea floor. This combination of two processing in one acquisition proved particularly useful in near shore site investigations where geotechnical investigations are quite difficult to perform.

Equipment and methodology

The acquisition for the high resolution seismic refraction and U-MASW has been performed using a bottom-towed acoustic source and a streamer of hydrophones. The spread included:

- An underwater sled hosting an airgun (20 cu.in), dragging a multichannel streamer (24 channels, 2m spaced),
- An umbilical for underwater-to-back deck communications,
- A set of back deck equipment: seismic recorder, gun trigger.

A penetration of 7 meters along the survey line was required and therefore guaranteed with this set-up. The distance between two consecutive shots was on average 20m.

U-MASW properties

In an infinite homogeneous continuum, only compression and shear waves are possible. The presence of a boundary in the continuum allows for a third type of wave. If the interface is between air and solid (i.e. a free boundary) the surface wave is of the Rayleigh type. If the interface is between water and solid the surface wave is of the Scholte or Stoneley-Scholte type. The particle motion of a surface wave is both compressional and rotational. For an introduction about theory of surface waves, the reader may refer to the extensive literature, e.g. Richart et al, 1970, and Stokoe et al, 2004.

The energy distribution in the soil varies depending on wavelength and is qualitatively shown in Figure 1. In the case of a layered medium, high frequencies (i.e. short wavelength) will travel with velocity of the shallow layers, while low frequencies (i.e. long wavelength) will travel with velocities corresponding to the deeper layers. Consequently, the frequency content of the surface wave will change with distance from the source. This property of the surface waves is called "dispersion". The multichannel analysis of surface waves (MASW) utilizes the property of dispersion to generate a continuous profile of soil stiffness below sea floor.

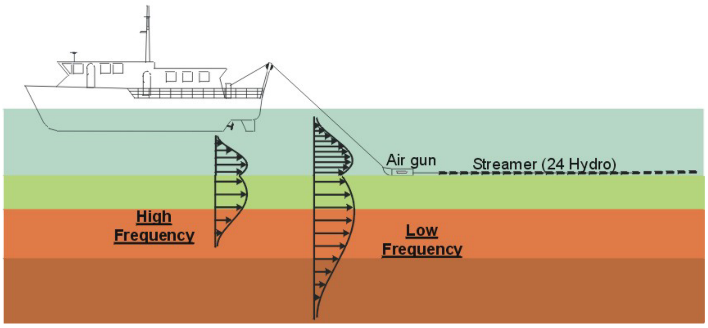
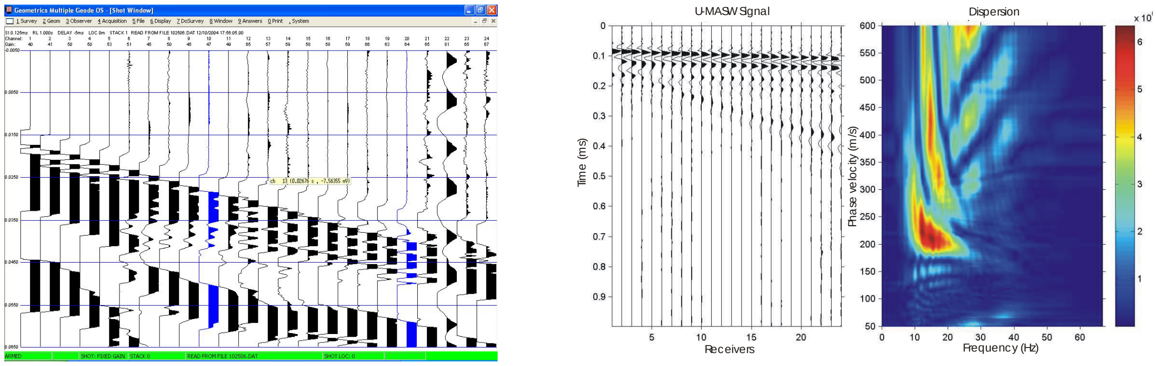


Figure 1: Methodology and U-MASW energy distribution in the sea floor.

Acquisition and QC control

If the QC of the seismic refraction acquisition is performed by the visualisation of the first arrivals that will be picked (figure 2a), for the surface wave QC, it is necessary to compute, for every shot, the energy distribution of the dispersion in order to be sure that fundamental mode used for the interpretation is well expressed (figure 2b). The figures here below show the QC for one seismic shot during the acquisition.



2a) 2b)

Figure 2a) QC for the refraction. 2b) QC for U-MASW - Seismic shot and dispersion quality control. The signal visualization and the energy distribution of the computed dispersion are shown.

Processing

The intercept time method was used for the marine refraction survey because the acquisition was limited at one shot per display (dynamic acquisition). Velocities are interpreted by determining straight-line (or nearly straight-line) slopes along the various portions of a time-distance plot of the first seismic arrival signal at the various geophone locations.

Processing of seismic surface waves data consisted of the following steps:

- Data filtering;
- Transformation of data from *x-t* plane to *v-f* plane, where *x* is distance, *t* is time, *v* is surface wave velocity and *f* frequency, by means of slant staking and FFT;
- The signal in the *v-f* plane generally shows the fundamental mode and higher modes. Only the fundamental mode, the slowest, was considered and picked as dispersion curve $v = v(f)$;
- Inversion from $v = v(f)$ to $v = v(z)$ where z is the depth below seafloor. The inversion process is repeated until the model and picked dispersion curve show a good match. The water layer is modelled considering the speed of sound, the density of water, and the water depth. The soil is modelled as a series of uniform horizontal layers and a substrate of infinite thickness.

Details about inversion methods are available in the literature (e.g. Foti, 2000; Strobbia 2003).

Results of survey

On U-MASW and refraction results presented here below, the horizontal axis is the PK or KP (in meters) defined for the project and the vertical axis is the depth (in meters).

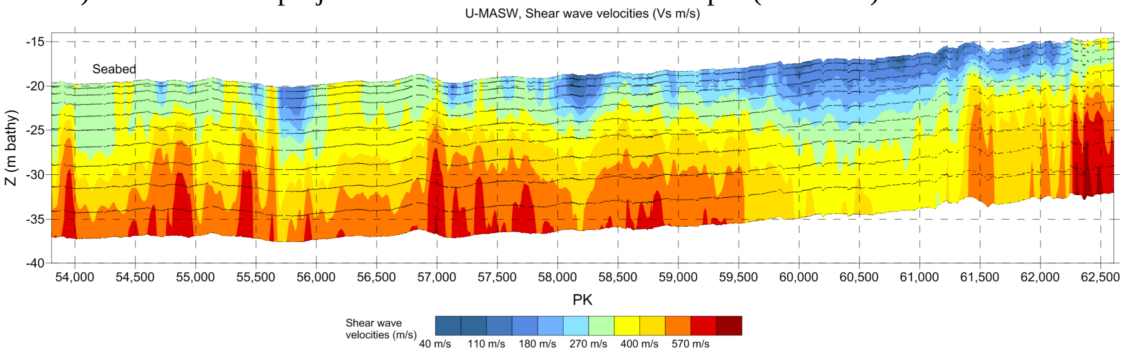


Figure 3: U-MASW results. The shear wave velocity computed is represented using a color scale.

The U-MASW processing permits to show:

- More or less gradient of the sediment shear wave velocity as a function of the depth.
- Local areas with low shear wave velocity (ancient channels).

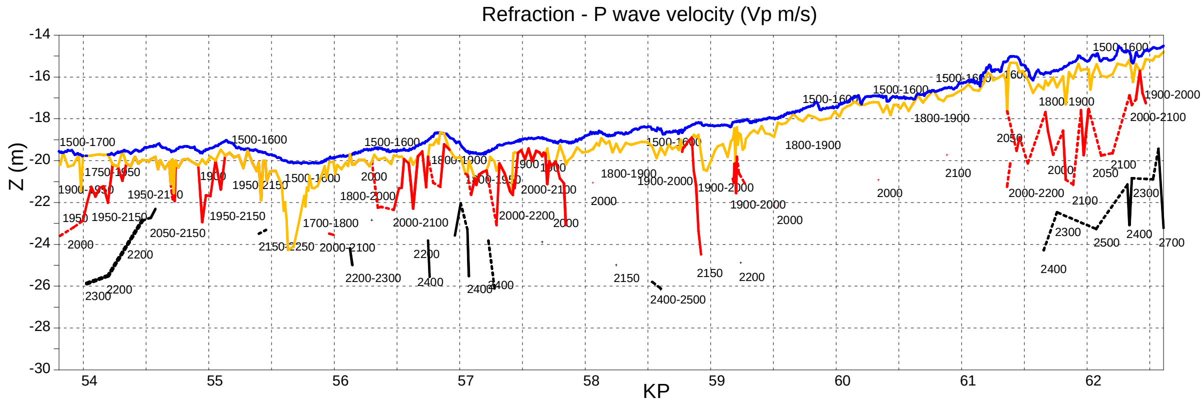


Figure 4: Refraction results.

The refraction processing shows on the whole line a first layer with a thickness varying from 1 to 2 meters and with a P wave velocity between 1500 and 1600 m/s. The higher P-wave velocities have been measured below this first layer with P wave velocities values varying between 1900 and 2400 m/s.

Combined interpretation of refraction and U-MASW

With the combination of the two processing it is possible to define seismic layers with different velocity properties corresponding to different kind of sediments or properties of sediment (more or less recent deposit or weathered sediment …).

To define the different seismic units, the P-wave velocity has been firstly used then in these units, the shear wave velocities permitted to define 4 or 5 units showing a stiffness gradient. In the first seismic refraction unit (Vp [1500; 1600 m/s]) 3 groups have been defined to distinguish different stiffness properties. The other layers have been defined according to the second or third refraction layers and the Vs variation depending on the depth and of the KP.

Units	P wave velocity (m/s)	S wave velocity (m/s)	Description (assumption)
#1	1500 – 1600	80 – 200	Recent deposit – sand and gravel
#2	1500 – 1800	200 – 300	Recent deposit – sand and gravel
#3	1500 – 1800	300 – 350	Outcrop of weathered moraine
#4	2000 – 2250	80 – 200	Weathered moraine
#5	1800 – 1900	100 – 200	Weathered moraine / Sand
#6	2000 – 2100	200 – 300	Weathered moraine
#7	1900 – 2250	300 – 570	Lightly weathered moraine
#8	Vp > 2300	270 – 400	Lightly weathered moraine
#9	Vp > 2300	Vs > 400	Lightly weathered moraine

Table 1: Description of the seismic units in function of the P and S wave velocities.

The figure below shows the obtained results.

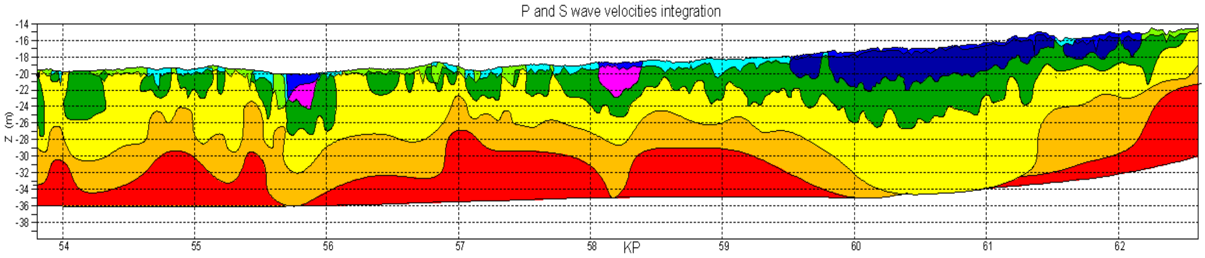


Figure 5: Integration of refraction and U-MASW results. The color scale used for the interpretation is detailed in table 1.

The first layer identified has Vp ranging around 1500-1600 m/s, and using the sonar interpretation this unit can be associated to sand and gravel. The unit #1 is softer than the unit 2, and the shear velocity measurement variation could be due to some variation of gravel density or gravel size. Due to the high shear wave velocity measured, the unit #3 has been identified as an outcrop of weathered moraine.
The second layer (units 4, 5 and 6) has the P wave velocity value between 1900 and 2200m/s and a shear velocity between 80 to 300m/s. Due to the local geology this layer could be a weathered moraine. The distinction of these 3 units is due to a shear gradient variation. The unit 6 presents an intermediate P wave and S wave velocity range. It could be weathered moraine or more compacted sand more.
The seismic units from #4 to #9 could be the moraine showing a gradient of weathered state.

Conclusion

This paper presents an application of a combination of seismic refraction and marine surface wave acquisitions where the data have been simultaneously collected and QC controlled during the survey. The results obtained show that this combined interpretation gives a more detailed description of the sediment.

Proceeding at a survey speed of about 2 knots, several km of survey can be executed in one day of operations. The combination of refraction and surface wave survey offer several advantages in this kind of project where the geotechnical investigations are quite difficult (currents, tide, waves …). Penetration is not limited by the water depth, while conventional methods are affected by multiple reflections which mask the acoustic signal in shallow water.

- Refraction: simple definition of the layers by their geometry and Pwave velocity measured.
- Surface wave: in a quasi-continuous mode, provides a shear wave velocity profiling along a route. Anomalous site conditions can be identified during the survey (stiffness gradient, velocities inversion,…). These waves penetrate in the soil also in the cases of a stiff layer overlying soft layers, and in presence of gas charged sediments.

These advantages make a combination of refraction and marine surface wave U-MASW particularly attractive in offshore surveys.

References

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