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Modeling and inversion of Scholte waves in shallow water for varying acquisition parameters

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Abstract

On land, surface waves are extensively and successfully used for the determination of Shear velocity profile (MASW). From those, the stiffness of the subsurface within 20-30 m can be derived, useful especially for engineering purposes. This technique can be effectively applied also to shallow marine environments: surface waves excited by air-gun and travelling along the sea-floor (Scholte waves) can be recorded by a receivers cable towed behind a ship. Acquisition parameters and the local setting of the marine environment (mainly water depth) have a strong control on the generation and detection of Scholte waves. In this work a finite-difference scheme has been used to model Scholte waves propagation for a simple 1D model, using several acquisition configurations. Based on inversion results and resolution of dispersion plots, the optimal acquisition parameters are derived. Moreover, the best strategy for acquisition in case of a laterally varying topography of the sea floor is defined. Since the strong 1D assumption for the inferring of Vs profile, more complex and laterally inhomogeneous models have then been implemented to test the effect of lateral variation on inversion results.

Acknowledgments

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The use of the FD modeling programme has been possible thanks to the kind help of its developer, Jan Thorbecke. His quick responses to my (numerous) questions were of great help.

Thank you Angela for your constant, trustworthy and essential support. Thank you Mamma and Papà for always trusting in me and my choices, this is of great motivation.

Chapter 1

Introduction

On land the determination of shear wave velocity (V_s) profiles by acquisition of source-generated, dispersive surface waves (MASW) is a well developed and established technique for geotechnical and engineering purposes. The shear wave velocity is in fact directly correlated to the stiffness of a soil; depending on the a priori knowledge of the site, several information can be then derived such as shear strength, lithology, compaction, clay content and presence of voids. In addition, a V_s profile within a depth of 30 m allows to determine the frequency response of a certain site, which is relevant for earthquake's risk remediation of constructions. In shallow marine environment, information regarding the stiffness of the shallower part of subsurface (max 30 m depth) can be equally relevant. The knowledge of the variation of shear strength with depth can be used when planning the locations of offshore wind-farm or oil-rig. Information about the encountered lithologies can be useful for locating and dredging sand bodies (used for mining, harbor creation and beaches nourishment). The same principle used for Rayleigh waves with the MASW technique on land can be transferred to the shallow marine environment. The equivalent of Rayleigh waves are in this case called Scholte waves (Scholte, 1947), traveling along the sea-floor with velocities slightly lower than those of Rayleigh waves due to the influence of the water layer. Similarly to the MASW case, the fundamental mode (that carries information about the dispersive behavior of surface waves) can be picked and inverted (assuming a 1D layered subsurface) obtaining a V_s profile of the subsurface.

The research institute Deltares (The Netherlands), where I have worked for my final Master thesis in Applied Geophysics, is particularly interested in the possibility of using Scholte wave to retrieve the shear wave velocity profile in shallow marine environments. In a reflection seismic survey acquired by Deltares in the Wadden sea, Scholte waves were observed only at certain locations where the water layer was

maximum 4 m thick (Kruiver et al., 2010). This suggests that either the power of the source (airgun) was not adequate to generate Scholte waves or the acquisition parameters were not suitable. The results is than that Scholte waves cannot be always successfully recorded, unless a proper acquisition setup is assured. The aim of this research is to retrieve the best combination of acquisition parameters to be able to detect Scholte waves in shallow marine environment. Acquisition parameters like *nearest offset*, *receiver spacing* and *spread length* will be investigated in case of a simple synthetic model. Once the optimal setup has been defined, the following step consists in testing this configuration for geometrically more complex, laterally inhomogeneous models.

Chapter 2

Previous knowledge on Scholte wave acquisition

Since Scholte waves are just the marine counterpart of Rayleigh wave, basically most of the know-how of the MASW technique can be transferred, at least as guide, to Scholte waves acquisition and analysis. Similarly to the MASW case, the typical work-flow for the analysis and processing of Scholte waves is:

- Acquisition
- Frequency filtering (to remove most of body waves events)
- Muting (if necessary)
- Generation of dispersion plot by 2D Fourier Transform
- Picking of fundamental mode (or higher modes if needed)
- Inversion of dispersion curve to retrieve shear wave velocity profile

In order to obtain reliable results, Scholte waves have to be adequately acquired. Therefore, all the parameters defining source and receivers should be accurately chosen. All the following requirements have to be assured:

1. ADEQUATE TEMPORAL SAMPLING

In order for the wavefield to be correctly reconstructed, it has to be adequately sampled in time. As general rule, the higher the frequency of the time signal, the higher the sampling rate should be. The Nyquist theorem states that the sampling rate (f_s) has to be at least double the maximum frequency contained in the signal (f_{max}):

$$f_s = 2f_{max} \quad (2.1)$$

If this criterion is not met, high frequencies are then aliased, introducing fictitious low frequencies in the acquired data. For seismic wave analysis, usually a sampling rate of 1-2 ms ($f_{max}=1-2$ kHz) is far enough sufficient to correctly acquire these seismic waves that usually have a frequency content far below 50 Hz.

2. ADEQUATE SPATIAL SAMPLING

The wavefield has to be adequately reconstructed in time as well as in space. According to the Nyquist theorem, at least two sampling points per minimum wavelength are needed. It means that the minimum wavelength that can be correctly acquired is dependent on the receiver spacing (Δx) according to the following equation:

$$\Delta x_{max} = \frac{v_{s(min)}}{2f_{max}} \quad (2.2)$$

where $v_{s(min)}$ is the minimum shear wave velocity. Fig.2.1 shows the effect of spatial aliasing on both seismograms and (phase-slowness, frequency) plot. In the top panel a shot gather with 20 m spacing and the derived slowness-frequency plot (on the right-hand side) are shown; the dispersive fundamental mode of Scholte waves is clearly aliased. When a finer, 5 m spacing is used, as shown in the bottom panel, the improvement in resolution in the dispersion plot is remarkable. A properly sampled wavefield generates a sharp and well defined dispersion curve allowing a good interpretation and less ambiguous picking.

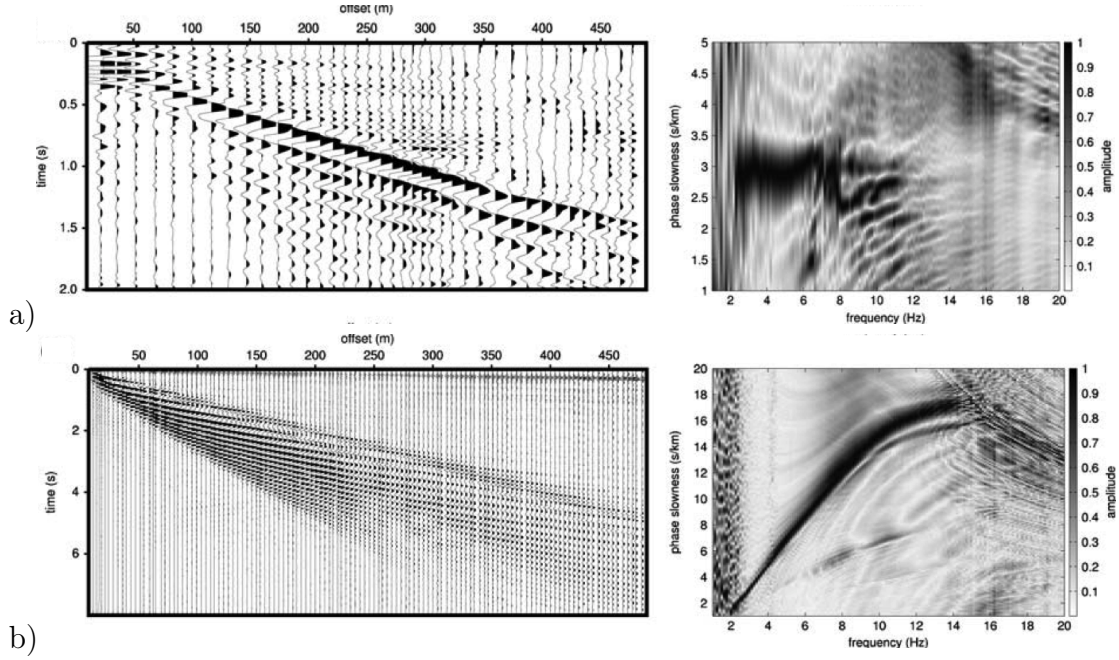


Figure 2.1: (a) Common Shot Gather with a 20 m receivers spacing. Note the effect of spatial aliasing on the slowness ($1/V_s$)-frequency spectrum on the right. (b) Properly spatially sampled Common Receiver Gather with a 3 m receivers spacing. The wavefield is correctly sampled, as testified by the (slowness/frequency) plot. (from Klein et al., 2005)

3. POWERFUL AND LOW-FREQUENCY SOURCE

As all surface waves, Scholte waves have a rather narrow low-frequency band, between 2-20 Hz. It means that sources with a low frequency signature should be preferred for their generation. This requirement is usually met using powerful sources, that also assure a good S/N ratio. It is generally suggested to use airguns for Scholte wave acquisition because those are powerful and generate adequate low-frequency energy. As example, a 0.6 l airgun is demonstrated to be successful in 20 m water depth in case of loose material at the sea bottom (Bohlen et al., 2005).

The distance between the source and the sea-floor is a key parameters for the occurrence of Scholte waves. In fact, the closer the source to the water-sediment interface (0-5 m range), the more effectively evanescent P-wave are converted to propagating surface waves. This is demonstrated in Allouche et al., (2011) where it is shown that only if the ratio h/λ (where h is the source height over the sea-floor and λ is the dominant frequency of the wavefield in water) is small the source generated P-wave significantly converts to S-wave, giving rise to propagating Scholte waves along the sea-floor (*near-field* condition).

As a guide, in table 1 are listed the different characteristics of airgun used for Scholte waves acquisition in literature:

POWER	CENTRAL FREQUENCY (Hz)	WATER DEPTH (M)	APPLICATION	REFERENCE
120 inch ³	Not specified	70-130	Over-consolidated sediments	Park et al., 2005
2 liters	Not specified	20-23	Soft sediment	Wilken et al., 2009
0.6 liters	35 Hz	< 50	Compact sediment	Bohlen et al., 2005
0.6 liters	35 Hz	20	Soft sediment	Bohlen et al., 2007
10 inch ³	Not specified	0.5	Coastal environment, soft sediment	Kauffman et al., 2005
10 inch ³	Not specified	1	Coastal environment, soft sediment	Kauffman et al., 2005

Table 2.1: Summary of source characteristics for several Scholte wave acquisition surveys in the literature.

4. GOOD RESPONSE OF RECEIVERS TO LOW FREQUENCIES

For Scholte waves acquisition either a multichannel streamer or a Ocean Bottom Cable (or Sensor) is used. When using a streamer, 24 channels (or more) are used, towed behind a ship at a constant water depth. When dealing with the acquisition of surface waves, the least contamination by body wave is desired; usually either 8-10Hz or 4-4.5 Hz hydrophones are used to enhance the Scholte waves signal.

One of the crucial parameters to be adequately defined is the receiver spacing (Δx). As demonstrated in the previous paragraph, the receiver spacing has a strong control on the minimum wavelength (and highest frequency) that can be recorded without aliasing. Since unconsolidated sediment in marine environments can have S-wave velocities as low as 50-100 m/s, even a 0.5-1 m spacing might be necessary.

Experimental data as well as a forward modeling example (Klein et al., 2005) demonstrate that hydrophones should be placed within 4-5 m from the seafloor in order to adequately acquire the entire Scholte wave's spectra. In Fig.2.2 the displacement amplitude of Scholte wave is plotted as a function of distance from the sea-floor (situated at 25 m depth) for a frequency band ranging from 0 to 15 Hz. Especially for higher frequency the decay in amplitude for increasing distance from the sea floor is dramatic.

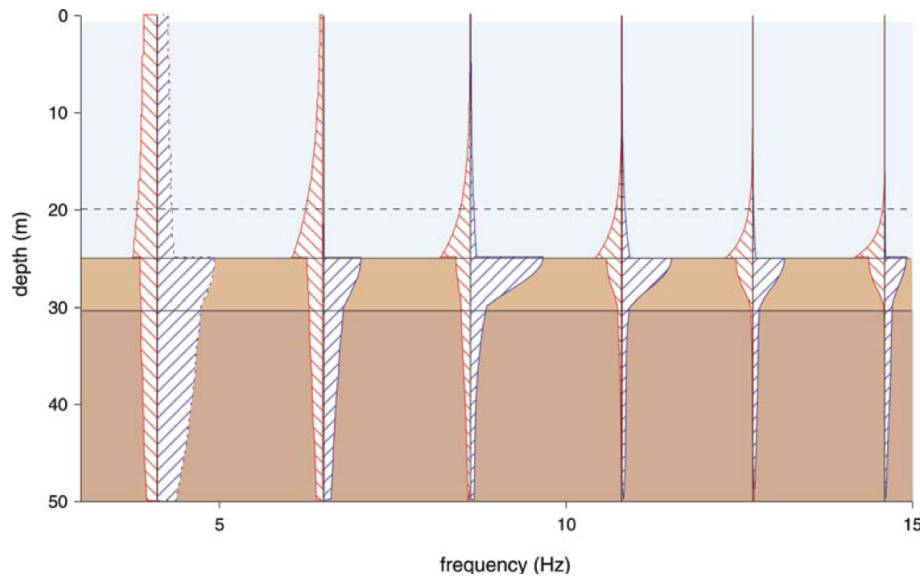


Figure 2.2: Vertical distribution of the squared displacement amplitude of Scholte waves for a simple model consisting in a 5 m thick, soft sediment layer overlaying a stiffer half-space. The red pattern is referred to the fundamental mode, the blue pattern to the 1st higher mode (from Klein et al., 2005).

Scholte wave can be acquired by streamer or deployed sensors on the sea floor. Both methods have advantages and disadvantages, which are listed below.

MARINE STREAMER

Pro's:

- easily and rapidly deployable
- small error on positioning
- fast acquisition

Con's

- the fixed receiver spacing bounds the maximum frequency detectable without aliasing, defining the minimum depth of a reliable information.
- noisy data due to continuous ship movement during acquisition
- acquisition parameters can be only partially modified

SEA-FLOOR DEPLOYED RECEIVERS

Data can be acquired with fixed receivers by varying source distance. In that case, geophones and hydrophones are placed on the sea floor providing good coupling and effective reconstruction of the elliptical particle movement of Scholte waves. Multiple shots are made in order to construct a receiver gather; as a result the resolution of the

acquisition only depends on shot distance increments and it can be varied according to the survey requirements. The main advantages and disadvantages of sea-floor deployed receivers are:

Pro's

- high response to Scholte waves (good S/N)
- possibility to vary parameters of acquisition depending on local characteristics of the subsurface

Con's

- difficult and time consuming positioning
- error on positioning
- limited horizontal range of information

Chapter 3

Methodology

3.1 Modeling

The finite-difference method has been used in order to solve the 2D wave equations and generate synthetic seismograms. The code 'fdelmod' has been developed by Jan Thorbecke, PhD at TUDelft (The Netherlands) and makes uses of the Seismic Unix (SU) parameter interface and output file (Thorbecke and Draganov, 2011). It is an open source code and can be used on UniX operative system. For the purpose of this work, the elastic scheme has been used therefore ignoring the effect of damping. The following equation are solved by finite-difference approximation:

Linearized equation of motion (Newton's second Law)

$$\frac{\partial V_x}{\partial t} = \frac{1}{\rho} \left(\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xz}}{\partial z} \right) \quad (3.1)$$

$$\frac{\partial V_z}{\partial t} = \frac{1}{\rho} \left(\frac{\partial \sigma_{xz}}{\partial x} + \frac{\partial \sigma_{zz}}{\partial z} \right) \quad (3.2)$$

Equation of deformation (Hooke's law)

$$\frac{\partial \sigma_{xx}}{\partial t} = \frac{1}{\kappa} \frac{\partial V_x}{\partial x} + \lambda \frac{\partial V_z}{\partial z} \quad (3.3)$$

$$\frac{\partial \sigma_{zz}}{\partial t} = \frac{1}{\kappa} \frac{\partial V_z}{\partial z} + \lambda \frac{\partial V_x}{\partial x} \quad (3.4)$$

$$\frac{\partial \sigma_{xz}}{\partial t} = \mu \left(\frac{\partial V_x}{\partial z} + \frac{\partial V_z}{\partial x} \right) \quad (3.5)$$

where σ_{ij} , V_i , κ , λ , μ are the symmetric stress tensor, particle velocity, compression modulus, Lamé's first parameter and shear modulus, respectively.

The first-order derivatives in space (lateral position x and depth position z) are approximated according to a 4th order Crank-Nicolson approximation meaning that 4 points are considered around $x=0$. For derivatives in time, a 2nd order scheme is used for approximation.

The finite-difference code automatically checks for stability and numerical dispersion. In order to assure stability, time steps and spatial discretization have to satisfy the following Courant criterion (Courant number=0.606 for 4th order spatial derivatives):

$$\Delta t < \frac{0.606 \Delta h}{c_{max}} \quad (3.6)$$

where Δt , Δh and c_{max} are time steps, discretization step in space and maximum propagation velocity respectively.

In order to avoid numerical dispersion, at least 5 points per minimum wavelength must be assured. Therefore, the following relation must be satisfied:

$$\Delta h < \frac{c_{min}}{5f_{max}} \quad (3.7)$$

where f_{max} is the maximum input frequency. It turns out that, if propagation velocities are decreased keeping the same frequency content, grid size must be decreased as well leading to higher computation time.

3.2 Subsurface model

In order to test the best acquisition parameters for Scholte waves, it has been decided to first implement a simple, laterally homogeneous model (called *standard model* throughout the work) consisting of a low velocity ($V_s=200$ m/s), 4 meters thick layer, overlaying a higher velocity ($V_s=600$ m/s) half-space in a shallow marine setting (6 m water depth). The grid size (in a staggered scheme) was set to 0.3 m, small enough to avoid numerical dispersion and assure stability of results. The model domain had always a dimension of 600 x 600 m with 200 m thick tapers except for the top of the model domain where a free-surface was set (simulating an air-water interface).

The computation time for each shot was roughly 40 minutes on a common Macbook Pro (2.4 GHz Intel Core 2 Duo, 4 GB DD3 Ram). In Table 3.2 the main modeling parameter are summarised for the standard model.

When decreasing the minimum propagation velocity of shear waves, the minimum wavelength is also expected to decrease ($v = \lambda f$) requiring a finer gridding to ensure stability of modeling. As a result, the computation time strongly increases for decreasing velocities (for the same frequency content of the input wavelet).

CENTRAL FREQUENCY OF INPUT WAVELET	43 Hz
INPUT WAVELET	Richter wavelet
TIME SAMPLING RATE	2 ms
RECORDING LENGTH	2 s
MODEL DIMENSION	600x600 m
GRID SIZE	0.3 m
TAPER THICKENESS	200 m

Table 3.2: Modeling parameters for the standard model.

In order to study the effect of velocities of the subsurface on the acquisition, both velocities of 1st layer and half-space have been decreased (100 m/s and 300m/s, respectively).

For the optimal acquisition set-up derived from modeling, an inclined sea bed was implemented with two acquisition strategies for Scholte waves: source and receiver at constant depth or following the inclined sea-floor topography. In addition to those, two laterally varying models (inclined interface and channel in-fill structure) have then been implemented in order to test the 1D inversion assumption.

3.3 Acquisition geometry for the standard model

The acquisition parameters that can be varied are several: depth of source and receivers, frequency content and power of the source, type of receivers and their resonant frequency, nearest offset, spacing of receivers, number of channel and according spread length. In this study, source and receivers have been kept always at a constant distance of 3 m from the sea floor (sufficient to generate and acquire Scholte waves as shown in Kruiver et al., 2010 and Allouche et al., 2011). Also frequency content of the source and response of receivers is maintained fixed.

The only acquisition parameters allowed to vary were:

- NEAREST OFFSET (x_1)

- RECEIVER SPACING (Δx)
- SPREAD LENGTH (x)

The results of the modeling of varying acquisition parameters are described in Chapter 4.

At a later stage the testing for these parameters is carried out for 50% lower V_s of the subsurface. In Fig.3.1 the first simple input model is shown. Based on inversion results, the best acquisition set-up for Scholte waves is decided. Additionally, more complex models have been implemented including laterally varying sea-bottom topography, dipping interfaces, channel in-fill structure. As a result, it has been possible to investigate how effective the acquisition set up is in scenarios closer to real world.

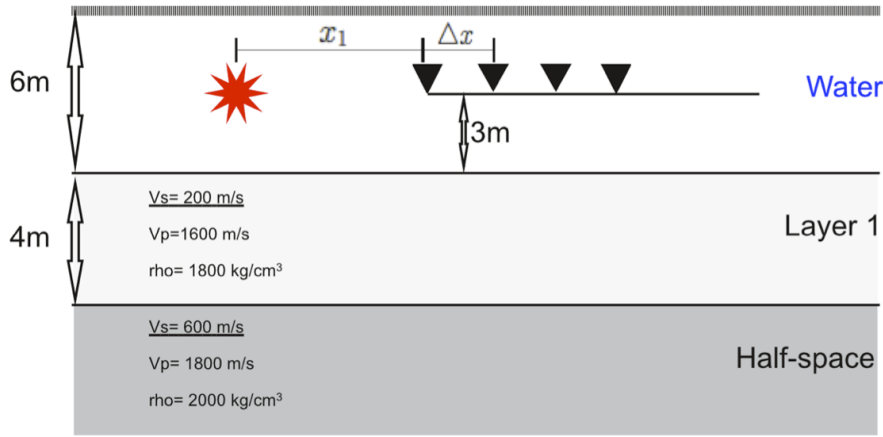


Figure 3.1: Standard model and source-receivers positions.

3.4 Processing

Frequency filtering

In order to enhance the Scholte wave signal, only *frequency filtering* was used. In Fig.3.2 an example of amplitude spectrum of one of the common shot gathers generated in our modeling studies. It can be noticed that the dispersive surface waves events are sharply separated from P-waves events (direct wave, reflections, refraction) in the frequency domain. Since Scholte waves have a low frequency content (dominant frequency around 18 Hz), a simple low pass filter <30 Hz has always been applied in order to enhance dispersive events and get rid of most of the P-waves energy. In Fig. 3.3 a filtered and an unfiltered common shot gathers are shown as example. Contrary to synthetic data, when dealing with real data, also surgical

muting might be necessary in addition to frequency filtering in order to improve the quality of the dispersion plots.

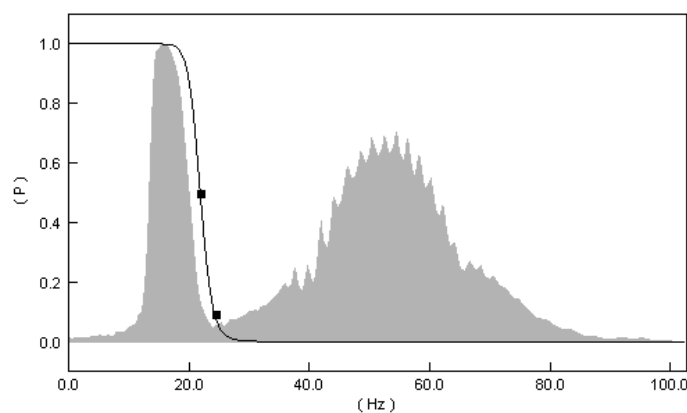


Figure 3.2: Amplitude spectrum of an unfiltered common shot gather with a nearest offset of 10 m and 48 channels at 1 m spacing. With a black line the low pass filter (<30 Hz) that has been used for all data is indicated.

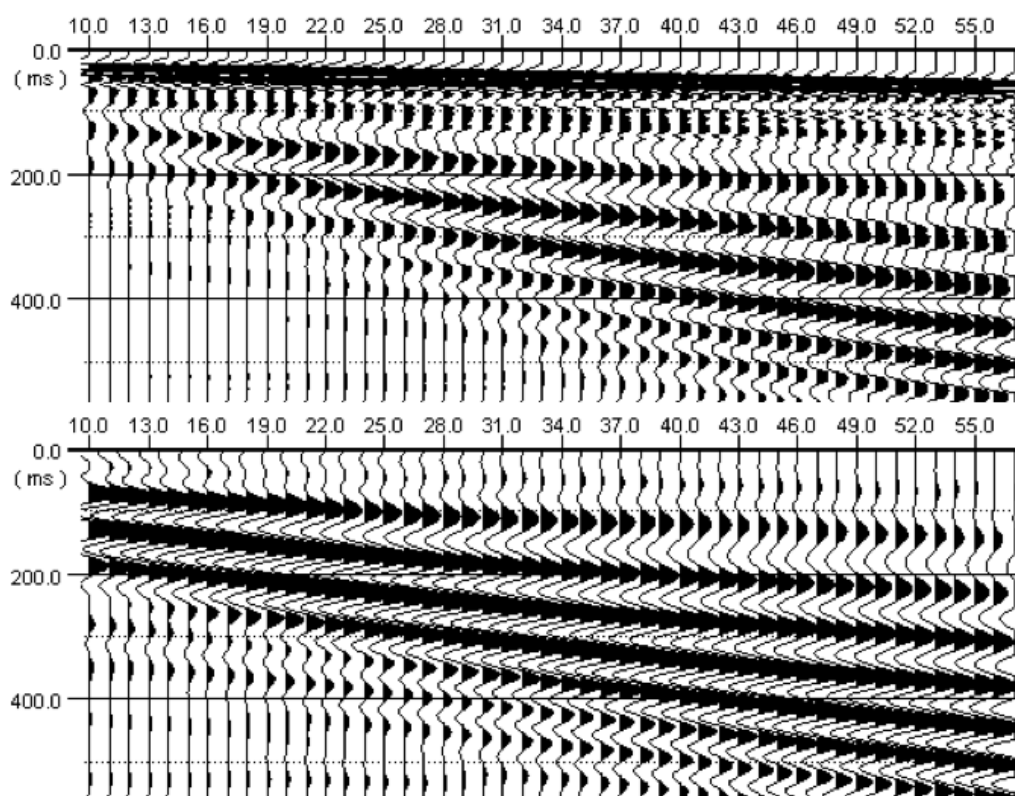


Figure 3.3: Unfiltered shot gathered in the upper figure. Below, the same shot gather after low pass filtering (<30 Hz). A nearest offset of 10 m and 48 channels at 1 m spacing are used.

Dispersion plot analysis and picking

Surfaces wave are defined as dispersive since each phase travels with different velocities depending on his frequency. Lower frequencies travel faster as they have higher penetration and being more sensitive to deeper (often stiffer) part of the subsurface. Contrarily high frequencies have scarce penetration and therefore travel with the (generally lower) velocity of the shallow part of the subsurface.

The dispersive behaviour of surface waves is studied analysing each shot gather according to the frequency-wavenumber (f,k) method. Here it is presented a brief explanation, from Park et al., (1998). Let's assume that $U(x, t)$ is the representation of a certain shot gather in the time-offset domain. This is first transformed in the space-frequency (x,f) domain by Fourier transform:

$$U(x, \omega) = \int_{-\infty}^{+\infty} u(x, t) e^{i\omega t} dt \quad (3.8)$$

where $\omega = 2\pi f$ is the radial frequency. $U(x, \omega)$ can be expressed as the multiplication of two separate term, $P(x, \omega)$ and $A(x, \omega)$. The first is the phase spectrum and contains all the information about dispersion properties; the latter is the amplitude spectrum and contains all information regarding attenuation and spherical divergence. Therefore $U(x, \omega)$ can be written as follows:

$$U(x, \omega) = e^{-iK_x x} A(x, \omega) \quad (3.9)$$

where an assumed K_x is the wave number in the x direction. The following integral transformation can be applied to $U(x, \omega)$ in the frequency-wave number domain (f, k_x):

$$V(\omega, k_x) = \int_{-\infty}^{+\infty} e^{ik_x x} [U(x, \omega) / |U(x, \omega)|] dx = \int_{-\infty}^{+\infty} e^{-i(K_x - k_x)x} [A(x, \omega) / |A(x, \omega)|] dx \quad (3.10)$$

The integral transformation can be seen as summation over different offset of a wave-field travelling with an assumed K_x . In order to compensate for different amplitude due to attenuation, $U(x, \omega)$ is normalised in the integral. For a given frequency a maximum is obtained when K_x is equal to k_x (the true wavenumber for a certain phase). In other word, the construction of a (f,k) plot can be explained as follow: considering a wave with frequency f , the direction of propagation x and a (assumed) velocity (or wavenumber K_x), the arrival time are calculated at all receivers and the phases are shifted according to the time delays. A wave that travels with a certain

frequency and velocity will stack constructively giving an high amplitude output, commonly called *beam power* (Capon, 1969). As a consequence, the locations of the maxima in the (f,k) plot give information about the velocity of each phase travelling along the receiver array. When analysing the dispersive behaviour of surface waves, (f,k) plots are difficult to read and to be interpreted; for this reason those are converted in phase phase velocity-frequency (v,f) plot by converting the wave number into velocity according to the following relation:

$$k_x = \frac{2\pi f}{v} \quad (3.11)$$

The freeware package Geopsy® (Wathelet, 2010), has been used to produce dispersion plots. It was also used for automatic picking (always preferred to avoid biases from the users) of fundamental mode. For displaying purposes, all plots are normalised by the total spectrum power. Even though a low pass filter was applied to the data, still some energy is always present above 30 Hz, referred to higher modes of propagation of Scholte waves. Their presence can be explained by the fact that the filter is not perfect and the amplitude value is not actually zero above 30 Hz. Nevertheless, those higher modes are not taken into account in our analysis and inversion. In Fig.3.4 an example of a dispersion plot with the picked fundamental mode is shown.

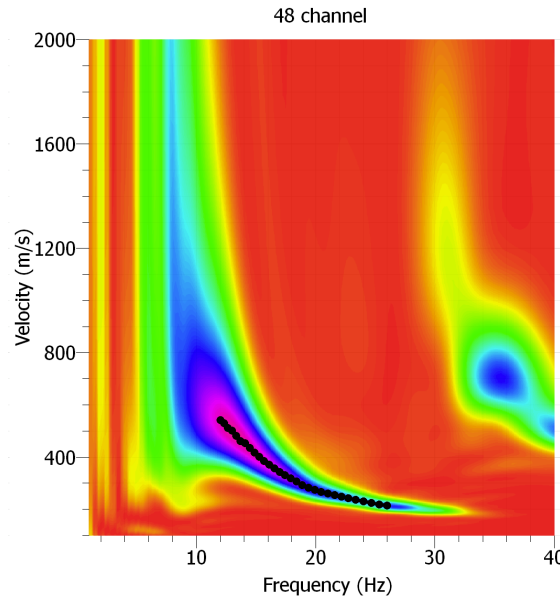


Figure 3.4: Example of dispersion plot and picked fundamental mode of Scholte waves (synthetic data)

3.5 Inversion

In order to obtain shear wave velocity profiles of the subsurface, the picked fundamental modes have been inverted with the software *"Dinver"*, part of the Geopsy® package already mentioned above. It is based on the neighbourhood algorithm, a stochastic direct-search method (Sambridge, 1999) and first applied in Wathelet et al., (2003) for the inversion of dispersion curves. Some input parameters are required. Therefore, a range of Vs, Vp, density, Poisson's Ratio and thickness have to be defined for a multilayer subsurface. No lateral variation can be included as the inversion code is based of a 1D layering assumption. In Table 3.3 the input parameters for inversion are listed; note the broad range of values in order to avoid biased inversion results due to the previous knowledge of the input model.

	Vs (m/s)	Vp (m/s)	Density (kg/m ³)	Poisson's Ratio	Thickness
LAYER 1	100-800	1500-2500	2000	0.3-0.5	0-20 m
HALF-SPACE	100-800	1500-2500	2000	0.3-0.5	-

Table 3.3: Input parameters for inversion.

Note that density has always been kept constant since its very small influence on Scholte waves propagation. It is in fact shown in Xia et al., (1999) that even a variation of 25% in density causes a very small perturbation of the fundamental mode, commonly less than 10%. No water layer can be included in the inversion algorithm. Nevertheless the receiver cable can be taken as reference when inferring the depth of interfaces.

Each dispersion curve is inverted with 10 runs. For each around 2.500 models are generated and investigated, for a total of 25.000 models for each shot. The goodness of a certain model is defined by the *misfit* function as defined in the following equation (Wathelet et al., 2004):

$$misfit = \sqrt{\sum_{i=1}^{n_F} \frac{(x_{di} - x_{ci})^2}{\sigma_i^2 n_F}} \quad (3.12)$$

where x_{di} is the velocity of data curve at frequency f_i , x_{ci} is the velocity of the calculated curve at frequency f_i , σ_i is the uncertainty of the frequency samples considered, and n_F is the number of the frequency samples.

Chapter 4

Variation of acquisition parameters

4.1 Variation of nearest offset (x_1)

4.1.1 Motivation

The position of source relatively to the first receiver can have a strong influence on the recorded surface waves. In particular, effects of *near-* and *far-offset* can be encountered. In the inversion routine, dispersive surface waves are assumed to be plane waves and this assumption can only be valid when surface waves have travelled a certain distance from the source. Near-offset effects are often observed when the source is not sufficiently far from the receiver spread leading to an incoherence of surface waves events in a shot gather. In real data, near-offset effect are recognisable by a lack of coherence of events and presence of fragmented energy packets (Park et al., 1999). To avoid this effect in the MASW case (on land), the following rule is proposed by Stokoe et al., (1994):

$$x_1 \geq 0.5\lambda_{max} \quad (4.1)$$

Nevertheless our goal is to check if this criterion is valid also in case of Scholte waves acquisition.

Moreover, since it is assumed that the maximum penetration depth of ground roll is roughly equal to its wavelength and the depth (z_{max}) at which shear wave velocity (V_s) can be calculated is equal to half of the wavelength, the following rule of thumb can be used:

$$x_1 \geq z_{max} \quad (4.2)$$

For the MASW case (on land) in Zhang et al., (2004) it is derived the following formula to select the optimal nearest offset, defined as the one that gives the best

resolution in the (v,f) domain:

$$x_1 = \frac{\lambda_{max} v_{min}}{4\Delta v} \quad (4.3)$$

It takes into account the maximum wavelength as well as the difference between the maximum and minimum shear wave velocities encountered in the subsurface.

As mentioned above, also an excessive distance between source and receivers might have an effect. High frequencies are more attenuated compared to low frequency as the wavefield propagates in space. This phenomenon is generally called far-offset effect and results in decreasing slope of surface waves events as offset increases leading to a reduction in coherence of traces at far-offset.

4.1.2 Modeling and results

To study the effects of nearest- and far-offset, 20 shots were modeled with a nearest offset ranging from 0 m to 80 m. The receiver spacing was set to 1 m for a total of 48 channels. In our case, Scholte waves showed a frequency content ranging from 11 to 30 Hz. According to the formula (eq. 4.1) proposed by Stokoe et al. (1994) given a minimum frequency of 11 Hz for a phase velocity of 600m/s, near-offset effects should not be observed if $x_1 \geq 27m$. In Fig. 4.1 two shot gathers are plotted acquired with a minimum offset of 0 m and 5 m respectively. For the 0 m offset case, the near-offset effect is observed. It can be noted that a value of 5 m for x_1 is already sufficient to avoid an undesired near-offset effect.

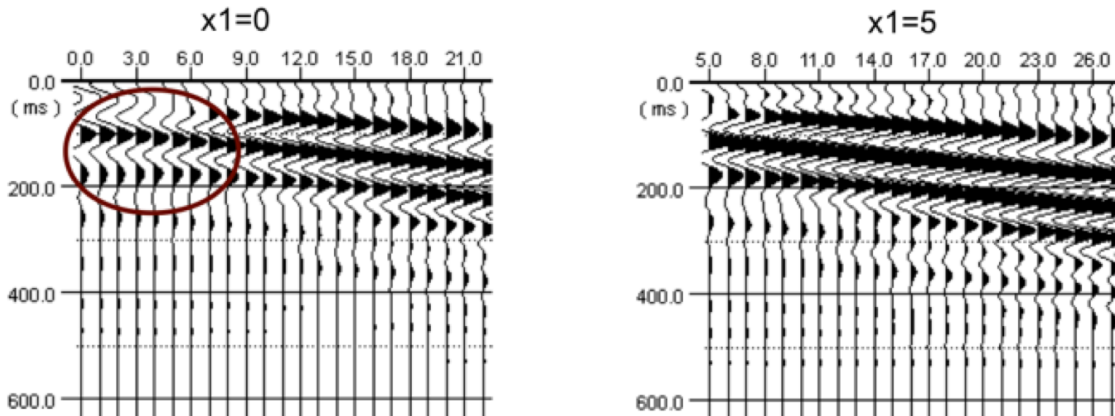


Figure 4.1: Comparison between two shot gathers for the standard model, with $x_1=0$ m (left) and $x_1=5$ m (right). 48 channels are used at 1 m spacing. Near-offset effect is reported in the red circle.

When increasing the nearest offset up to 80 m, far-offset effect have not been encountered. The reason for that is the elastic modeling scheme that has been used where no damping is implemented. Nevertheless, in real data surface waves are expected to be more attenuated compared to P-waves: in fact surface waves are strictly related to S-waves whose damping rate is actually higher than that for P-waves.

Relevant differences can be observed in the (phase-velocity/frequency) plots. In Fig.4.2 three dispersion plots (and the picked fundamental modes) referred to the $x_1=0$ m, $x_1=10$ m and $x_1=80$ m cases are shown. In the near-offset case ($x_1=0$ m) the fundamental mode is less resolved (amplitude is more smeared out within a broader range of velocities) compared to the large offset case.

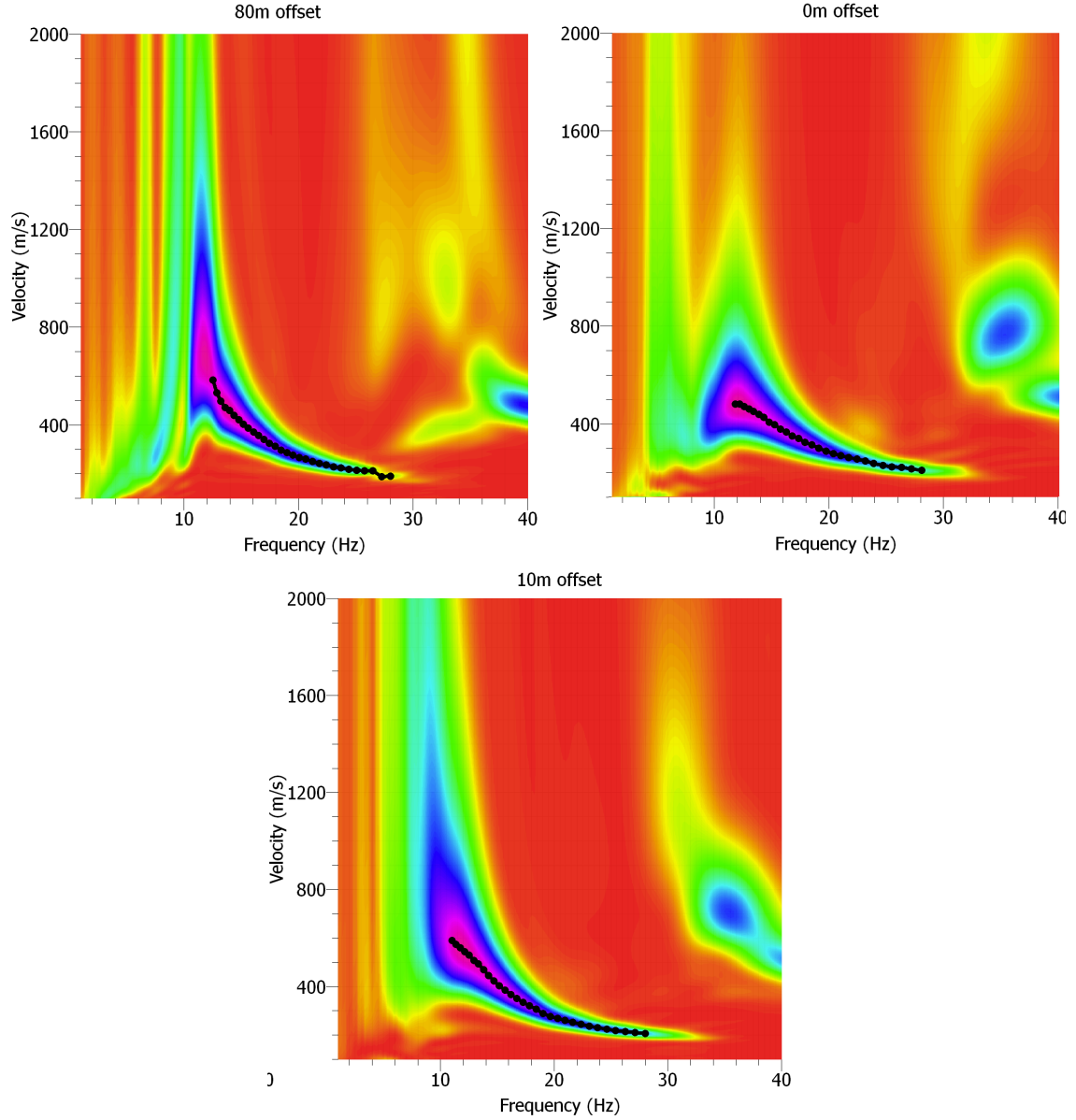


Figure 4.2: Comparison of phase velocity/frequency plot using three values as nearest offset: $x_1=0$, $x_1=10\text{m}$ and $x_1=80\text{m}$ for the standard model. 48 channels at 1 m spacing are used. Note the increased sharpness of fundamental mode for the larger offset. Nevertheless, in both cases the higher modes are poorly resolved.

It is worth noticing that in both the limit cases, higher modes are poorly resolved. In Fig.4.3a the auto-picked dispersion curves for different values of x_1 are plotted. Several differences are present especially in the lower frequency range ($f < 15\text{ Hz}$) for values of x_1 ranging from 0 to 30 m. It is expected that differences can be seen also in the inversion results since the relevant variation in shape of the picked fundamental modes. In Fig.4.3b, the inferred values of shear waves velocity of layer1, half-space and depth of the interface between those are shown. The shear wave velocities of

the two layers are extremely well constrained when x_1 ranges from 60 m to 80 m whilst the depths of the interface are clearly underestimated for the same range. For short offset (0 and 5 m) inferred depth is also strongly underestimated.

According to the inversion results, a good compromise would be a nearest offset value of 10 m since both depth and shear wave velocities of the two layers are well constrained. Moreover, both fundamental mode and 1st higher mode are sufficiently sharply resolved in the (v,f) plot to allow a simple and less ambiguous picking.

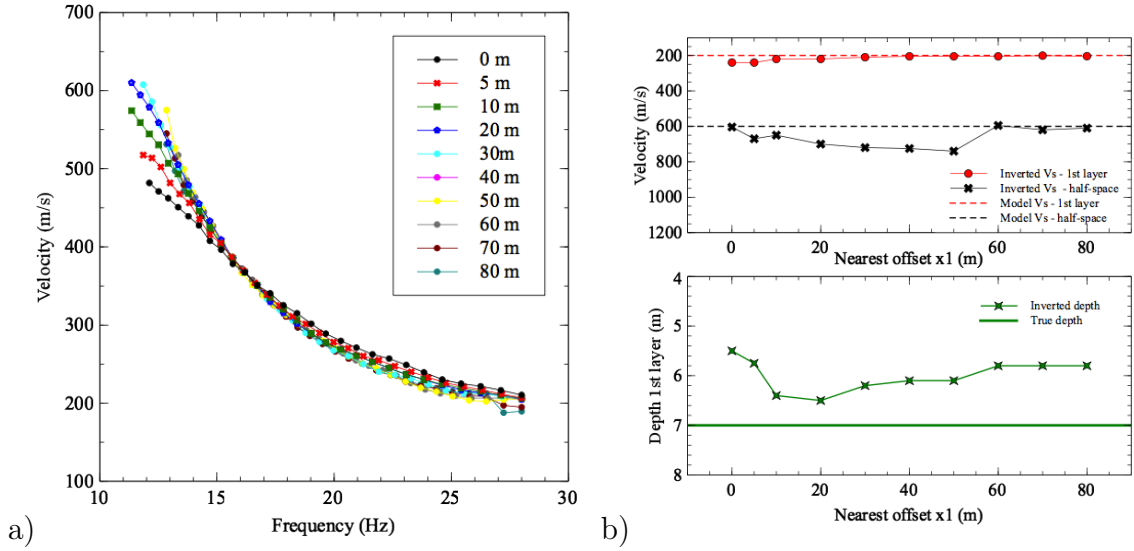


Figure 4.3: a) Picked fundamental mode for nearest offset (x_1) ranging from 0-80 m.
b) Inversion results (Shear waves velocities, depth of the interface between layer 1 and half-space) depending on nearest offset (0-80m).

When dealing with dispersive surface waves, acquisition parameters are site-specific and a rough previous knowledge of the subsurface is necessary in order to correctly acquire Rayleigh waves. Applying eq. 4.3 to our input model, a value of $x_1=10$ m is obtained, the same value that, from our modeling results, appears to be optimal for Scholte waves in terms of inversion results and resolution of both fundamental and higher modes. Nevertheless the derived value is in contrast with the one obtained applying eq. 4.1. This discrepancy could be explained by the fact that eq. 4.1 is a simple rule of thumb that therefore should be used carefully as it does not fully take into account the condition of the subsurface. On the contrary, eq. 4.3 contains Δv , the difference between the maximum and minimum Vs in the subsurface, likely leading to a more accurate result.

4.2 Variation of receiver spacing (Δx)

4.2.1 Motivation

In this section, the effect of variation of receiver spacing (Δx) on Scholte wave acquisition will be investigated. It is expected that the dispersive Scholte wavefield is not properly sampled in space with a too coarse receiver spacing, leading to aliasing effect. As a rule, receiver spacing should be at most half of the minimum wavelength (eq. 2.2). In the case of our input model (minimum $V_s=200$ m/s, maximum $f=30$ Hz) the minimum recorded wavelength is 6.7 m, requiring a maximum receiver spacing of 3.3 m receiver spacing. It is clear that, similarly for nearest offset, the optimal value for Δx depends on local condition of the subsurface (lower Shear wave velocities require smaller spacing) as well as frequency content.

4.2.2 Modeling and results

According to the results obtained in the previous section, a value of $x_1=10$ m for nearest offset was used. Four different values of receiver spacing were tested (**0.5 m**, **1 m**, **2 m** and **4 m**). In order to study the only effect of spacing on Scholte waves acquisition, the cable length was kept constant a 192 m varying the channel number accordingly, as shown in Table 4.1.

Receiver spacing (m)	Channel no.	Tot. Spread length (m)
0.5	384	192
1	192	192
2	96	192
4	48	192

Table 4.1: Aquisition parameters for receiver spacing modeling.

In Fig.4.4 the (v,f) spectra are shown for the different receivers spacing. The area below the black line is the aliased region where fictitious events can be observed due to the coarse receiver spacing. Nevertheless, fundamental modes appears not to be influenced by spatial aliasing at least, for Δx up to 4 m. For $\Delta x=4$ m, the higher mode (due to its higher frequency content) partially lies in the aliased region.

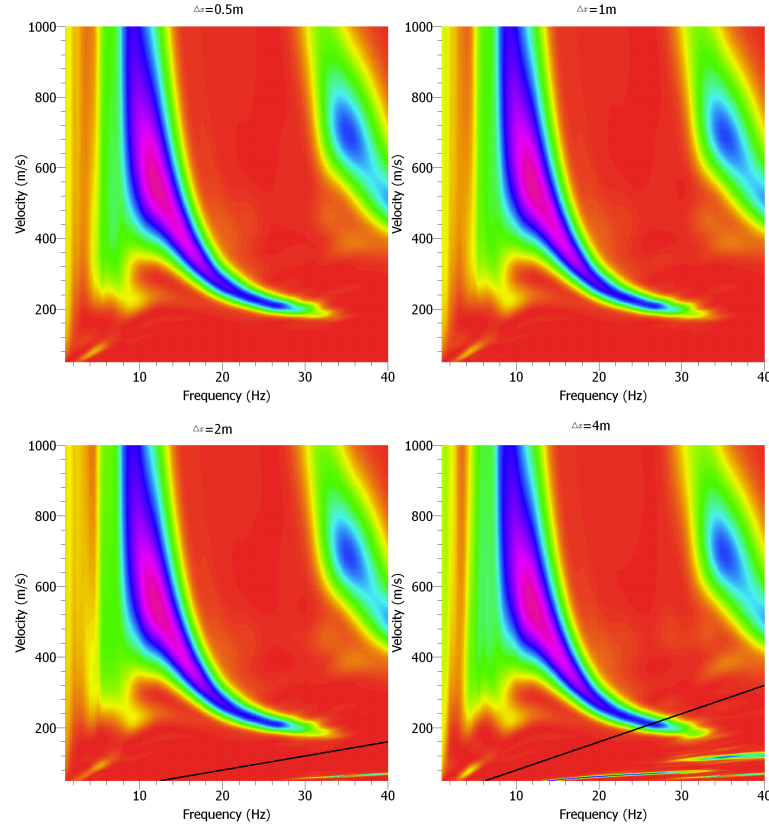


Figure 4.4: (Phase-velocity/frequency) plot for several value of receivers spacings for the standard model. A nearest offset $x_1=10$ m and a total spread length of 192 m are used. The black line indicates the spatially aliased region.

The automatic picking resulted in identical dispersion curves for the fundamental modes leading to the same inversion results for all the cases. In conclusion, for the standard model, a receiver spacing up to 4 m is sufficient to correctly retrieve the the fundamental mode. Contrarily, if higher modes are required for inversion and have to be correctly sampled, Δx should not be higher than 2 m.

The required receiver spacing to avoid aliasing is strongly dependent on the encountered Vs of the subsurface (the lower Vs, the smaller the the wavelength and the smaller the required spacing) for the same input frequency. The effect of lower the velocities on the determination of the optimal value for Δx will be investigated in Chapter 5.

4.3 Variation of spread length (x)

4.3.1 Motivation

In the following section the effects of variation of channel number on Scholte waves acquisition will be investigated. It is expected that better results would be obtained for a long receiver spread, because different phase velocities have the possibility to better separate as the wavefield propagates in space along the receivers array. As a result, with a longer spread length the (phase-velocity/frequency) plot would show an increased resolution, resulting in sharper fundamental and higher modes (consequently, easier to pick and prone to less uncertainty).

4.3.2 Modeling and results

Four different spread lengths (with **24**, **48**, **72** and **96** channels, respectively) have been tested for a fixed nearest offset and a receiver spacing, 10 m and 1 m respectively. When analysing the the v/f plots the strong influence of spread length on acquired Scholte waves can be appreciated as in Fig.4.5. With 24 channels, the receiver spread is definitely not long enough for different phase velocities to separate. It results in a broad and poorly resolved fundamental mode.

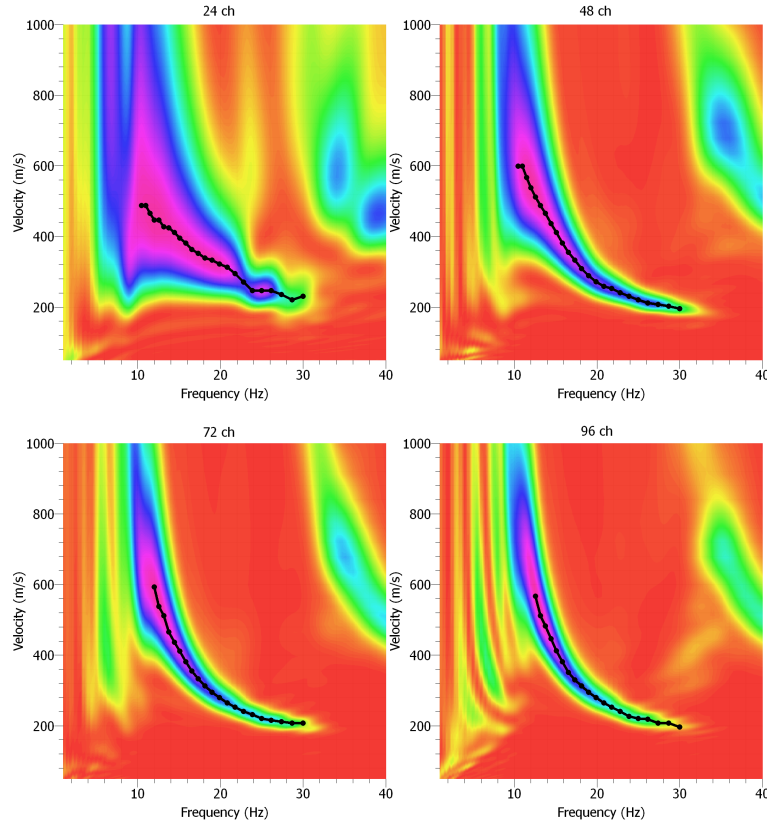


Figure 4.5: Phase velocity plots for different spread lengths for the standard model. An nearest offset of 10 m and a receivers spacing of 1 m are used.

However, for 48 channels, the improvement in resolution is dramatic. The best results is, as expected, obtained for the 96 channels case. Substantial differences are present in the auto-picked fundamental mode, as shown in Fig.4.6a. The difference between the dispersion curve for 24 channels and the ones retrieved with a higher number of channels appears to be relevant. Considering the inversion results (Fig.4.6b), while velocities of the 2 layers are well constrained, the depth of the boundary between 1st layer and half-space is strongly underestimated (more than 30%) when 24 channel are used. Again, the best result is obtained when using 96 channel for both shear wave velocities and depth determination.

All inversion algorithm for Vs profile determination are based on 1D layering assumption, meaning that no lateral variations in properties can be taken into account. Therefore, in both land or marine settings, when dealing with dispersive surface waves, the spread length is suggested to be kept as short as possible in order for the 1D layering assumption to remain valid. A long spread length leads to a strong averaging of the lateral inhomogeneity of the subsurface leading to loss in lateral resolution. Therefore, as trade-off among resolution of the (phase-velocity/frequency)

plots, inversion results and shortness of spread length, it can be concluded that the optimal channel number to be used is between 48 and 72 meaning a spread length ranging from 47 m to 71 m at 1 m spacing.

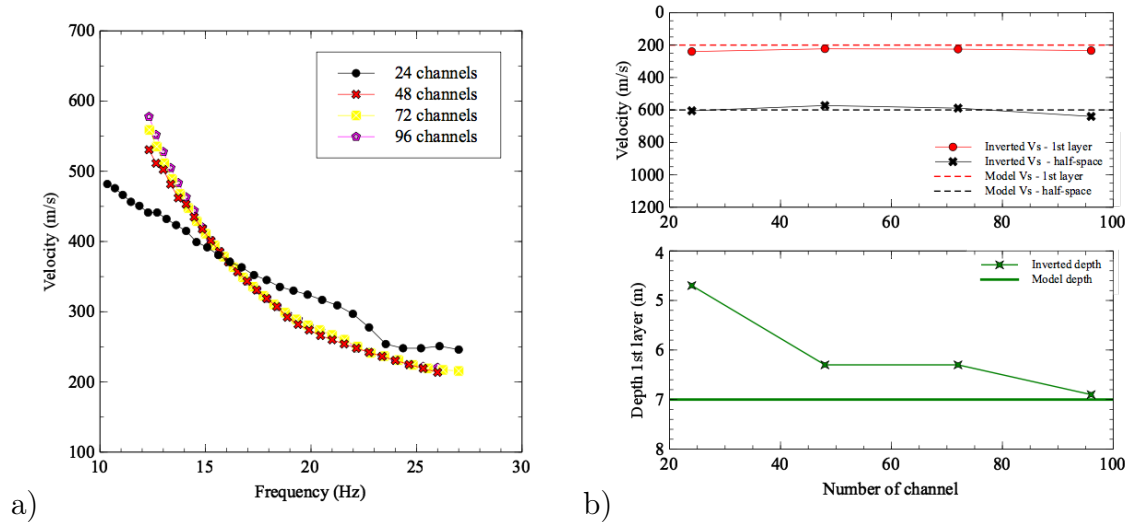


Figure 4.6: Auto-picked dispersion curves (a) and inversion results (b) for different channel numbers (and according spread length).

Chapter 5

Slower velocities model

5.1 Motivation

So far a minimum shear wave velocity of 200 m/s has been implemented for the 1st layer in the standard model. In the coastal environment, this velocity is generally encountered in case of loose sand in the shallower part of the subsurface. Variation of compaction, sorting and pressure may lead to variation of this value. Finer and less stiff material can be present in shallow water environment. In this case the V_s are expected to be much lower than 200 m/s. For muddy sediments shear wave velocity can be as low as 100 m/s and, in case of peat, V_s can reach a value of 30-50 m/s.

Shear wave velocities of the subsurface can have a strong control over the optimal acquisition parameters for Scholte wave acquisition. In particular, the Nyquist theorem should be always fulfilled in space in order to assure a correct spatial sampling of the dispersive wavefield. It means that lower propagation velocities require short receiver spacing for the same frequency band.

In the following section it will be investigated the effect of lower shear wave velocities (100 m/s and 400 m/s for the 1st layer and half-space, respectively) upon the optimal values for nearest offset, spread length and receiver spacing.

5.2 Variation of nearest offset (x_1)

It has been decided to test various values of nearest offset, ranging in total from 0 m to 30 m. The reason for that is the fact that usually values for $x_1 > 30-40$ m are hardly applicable and not suggested for acquisition of real data; the damping of Scholte waves would be rather severe not allowing a proper recording of those. In Fig.5.1 the dispersion plots for a nearest offset of 0m, 10m and 30 m are shown. The

resolution of the fundamental modes appears to be optimal already with 0 m offset and it actually worsens when longer nearest offset are used. This is in contrast with what observed in the case of the standard model where a for $x_1=0$ m the fundamental mode was affected by a poor resolution as well as a different shape if compared to those of longer nearest offset.

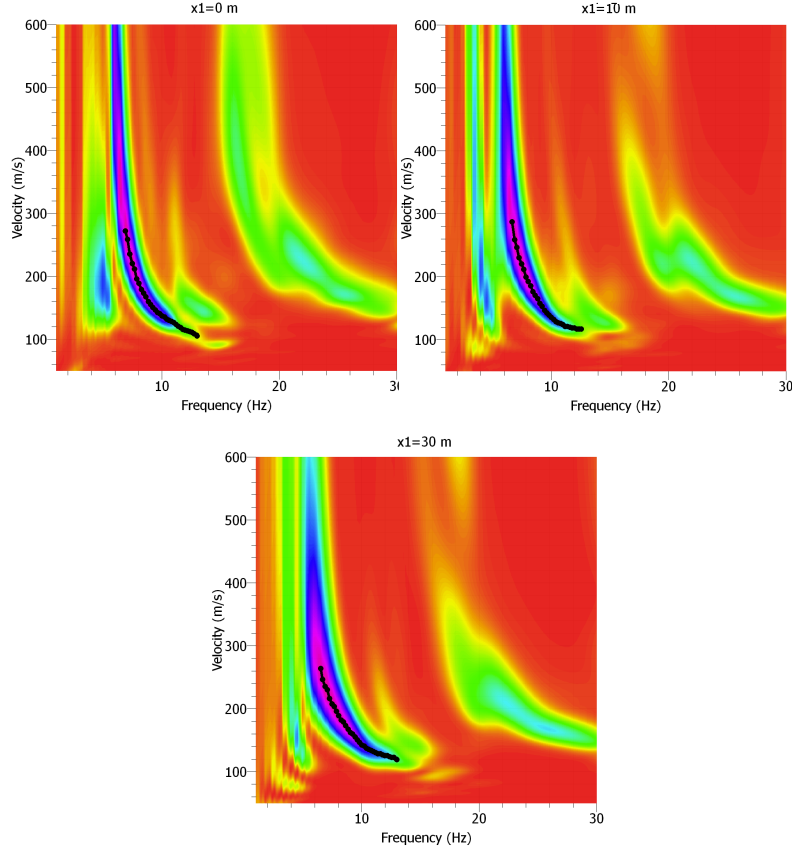


Figure 5.1: Dispersion plots for 3 different values of nearest offset (0 m, 10m and 30m) for a (modified) standard model with 50% lower shear wave velocities. 48 channels at 1 m spacing are used.

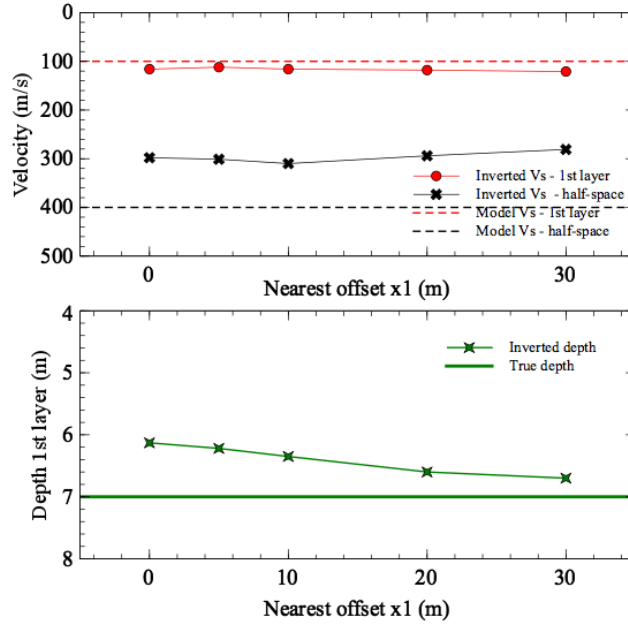


Figure 5.2: Inversion results for values of nearest offset ranging from 0 m to 30 m with 48 channel at 1 m spacing in case of a model with 50% lower shear wave velocities than the standard model.

In Fig. 5.2 the inversion results for varying x_1 are shown. The depth determination of the interface between 1st layer and half-space improves with larger offset while shear wave velocity becomes more underestimated. Nevertheless a value of $x=10$ m (considered as optimal in the case of the standard model) can be still considered as a good compromise also for rather lower velocities of the subsurface.

5.3 Variation of receiver spacing (Δx)

As previously stated, the required receiver spacing to avoid spatial aliasing is strongly dependent on the encountered Vs of the subsurface (the lower Vs, the smaller the minimum wavelength and the smaller the required spacing) for the same input frequency. Again, four values of Δx have been tested (0.5m, 1 m, 2 m and 4 m). It is expected a much clear influence of receivers spacing on spatial aliasing. Firstly, it should be pointed out that the Scholte waves frequency content for this case is rather shifted toward lower frequencies compared to the case of the standard model. In Fig. 5.3 it is shown a comparison between the frequency spectra (before low-pass frequency filtering) for the standard model and the one with 50% lower Vs.

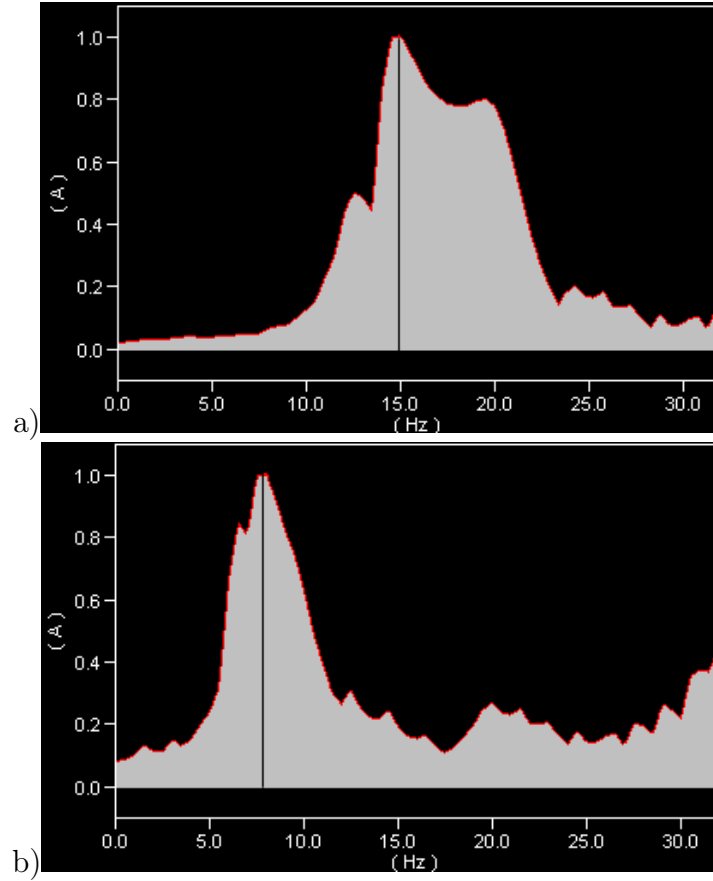


Figure 5.3: a) Frequency spectrum of Scholte waves when using the standard model (minimum $V_s=200$ m/s). b) Frequency spectrum of Scholte waves when implementing a model with 50% lower velocities. Both spectrum are referred to to raw, unfiltered data.

The first spectrum shows a dominant frequency of around 15 Hz whilst, for lower V_s , it is roughly 7-8 Hz. This phenomenon has a quite important implication that can be appreciated in the (v,f) plots for varying receiver spacing. In Fig. 5.4 the dispersion plots for the four different receiver spacings are shown. It can be noted that, given the shift of the Scholte waves frequency band towards lower frequencies, the fundamental mode still lies in the un-aliased region, even in the case of the largest receiver spacing ($\Delta x=4$ m). Therefore, surprisingly, a lower velocities of the subsurface seems not to require a finer sampling in space. The decrease in propagation velocity is in fact compensated by a lower frequency content ($c = \lambda f$) avoiding a significant decrease of the minimum wavelength. As for the standard mode, only the 1st higher mode was affected by aliasing when the coarsest receiver spacing (4 m) was used.

It can be concluded that the optimal value of receiver spacing obtained for the standard model remains fully feasible in case of slower shear waves velocities in the

subsurface.

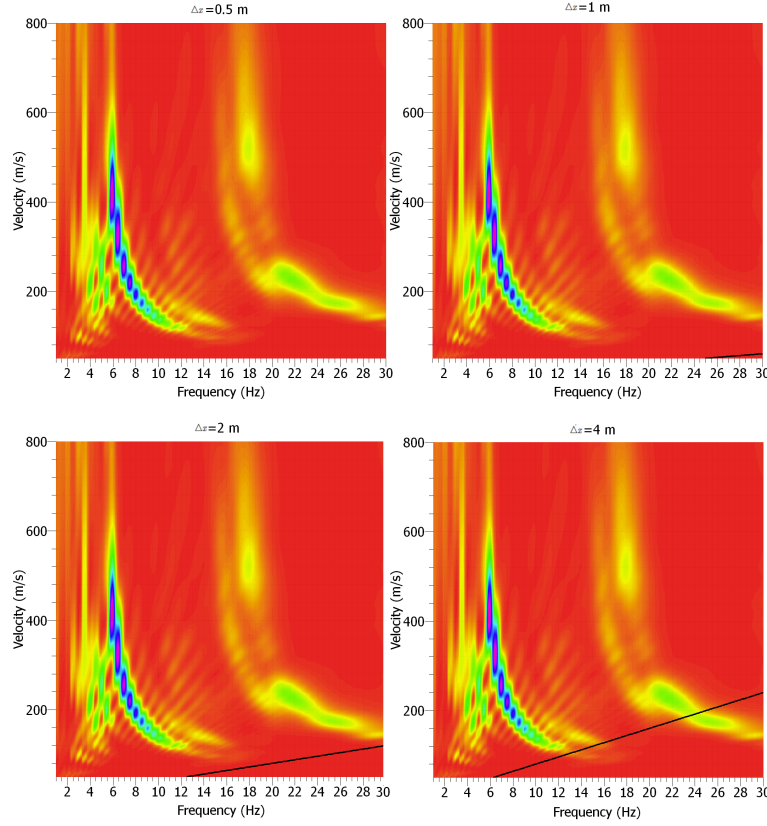


Figure 5.4: (Phase-velocity/frequency) plot for different values of receiver spacing in case of lower shear wave velocities (100 m/s and 300 m/s for the 1st layer and half-space, respectively). A nearest offset of 10 m and 192 m spread length are used. Note the difference scale of both frequency and phase-velocity axis compared to plots in Chapter 4.

5.4 Variation of spread length (x)

Similarly to the case of the standard model, four different spread lengths have been tested: 24, 48, 72 and 96 channels. Again, receiver spacing was set to 1 m and nearest offset to 10 m. In Fig. 5.5 the (v,f) plots are shown for each of the spread lengths. As already observed when using the standard input model, a clear increase in resolution of the fundamental mode is observed when increasing the channel number. In fact, an increased spread length allows a better separation of different phases (that travel with different velocities) improving resolution of the fundamental mode. Nevertheless, for 50% lower shear wave velocities, this improvement is less prominent compared to that obtained for the standard input model (higher propagation velocities).

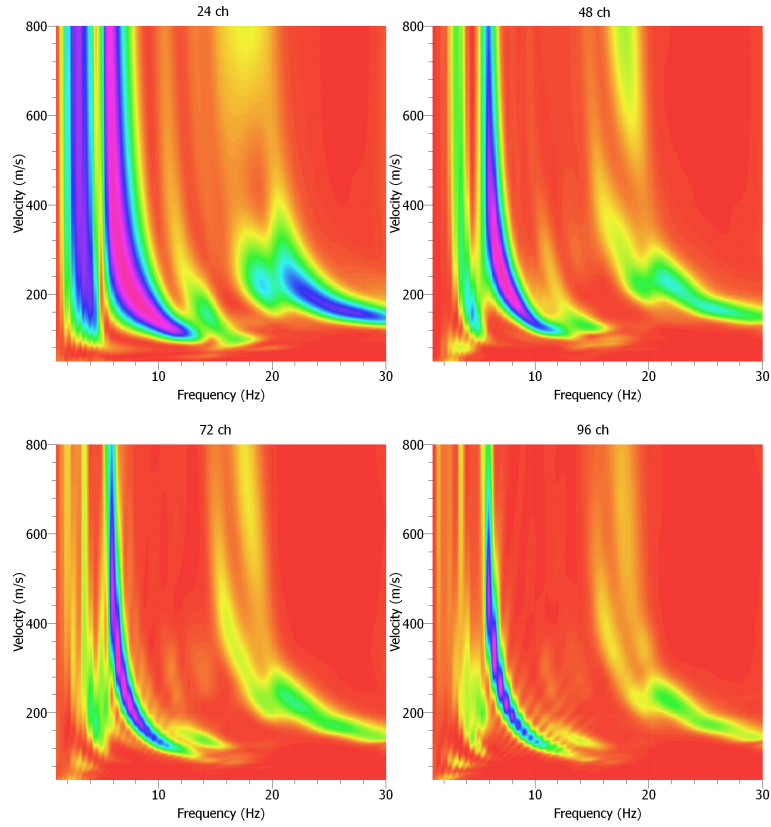


Figure 5.5: Phase velocities/frequency plot for different spread lengths for a model with 50% lower shear wave velocities compared to the standard model. 48 channels a 1 m spacing are used with a nearest offset of 10 m.

In Fig. 5.2 the inversion results for the four different spread lengths are shown. The inferred V_s profile for varying channel number are rather equivalent. In all cases the velocity of the half-space is underestimated while the depth of the interface between that and the overlying layer is very well inferred in case of short spread length (relative to 24 and 48 channels). Those results are rather different from those obtained for the standard input model: the shortest spread (24 channel) led to a strong error especially for the depth determination whilst in this last case a 24 channel give results as good as the longer spread.

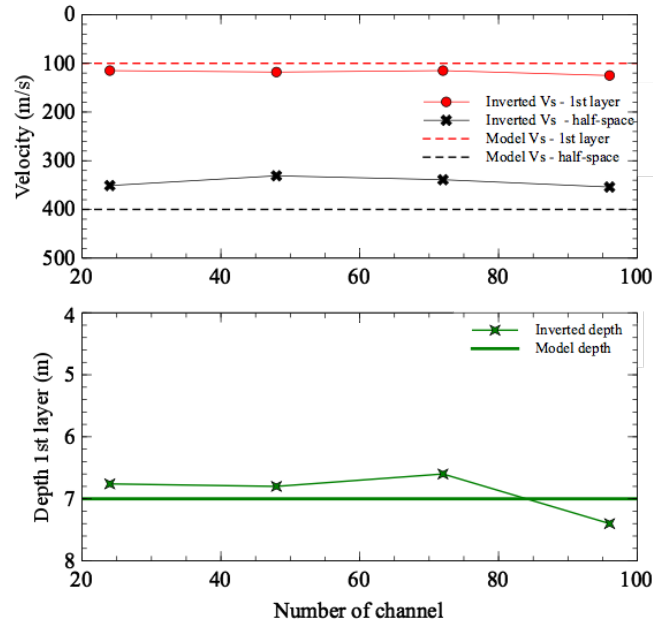


Figure 5.6: Inversion results for varying spread lengths in case of a model with 50% lower shear wave velocities compared to the those of the standard model.

An explanation would be the following: higher propagation velocities need longer travel path for events to be separated compared to low propagation velocities, for which a shorter spread would suffice. As a consequence 24 channels did not suffice for the higher velocity case; on the contrary, for the lower velocity model, 24 channels appear to correctly retrieve the fundamental mode, similarly to the longer spread. Concluding, in case of lower velocities encountered in the subsurface, the rather similar inversion results for different spread lengths confirm what observed in the (v,f) plots. The difference in shape and resolution of the fundamental mode when varying spread length are negligible and lead to equivalent inversion results.

Chapter 6

Strategy for a varying sea-bottom topography

6.1 Motivation

So far a simple 1D model model has been implemented. No lateral variations were encountered and both the sea-bottom and the interface between 1st layer and half-space were horizontal. This scenario is obviously far from reality. Sea-bed topography can be highly variable at different scales and the subsurface can be characterised by prominent lateral inhomogeneity.

Klein et al. (2005) showed that the displacement amplitude of Scholte waves strongly decreases with increasing distance of receivers from the sea-floor. The overall amplitude and its decrease depends on frequency (higher frequencies are attenuated more than lower frequencies) as well as stiffness of the subsurface; a maximum distance of 5 m of receiver from the sea-floor is suggested to be used.

Also the source should be placed as close as possible to the sea-bottom in order to assure an effective generation of dispersive surface waves. In general as a rule of thumb, the source should be placed from the sea-floor within a half of the minimum wavelength of the propagating wave in the fluid.

In this section, a gently sloping sea-bed is implemented in the standard model in order to investigate the influence of distance of source and receivers from the sea-bed on Scholte waves acquisition and inversion. This acquisition strategy is then compared to the case of source and receivers placed at different depth, following sea-floor topography.

6.2 Modeling

The acquisition parameters for the inclined sea-bed are those defined as optimal in Chapter 4. Therefore a nearest offset of 10 m, 48 channels at 1 m spacing have been used. This combination also assures the shortest spread length possible, to reduce the effect of lateral inhomogeneity.

The input model consists of a 1st layer overlying a half-space with same S-wave velocities, P-wave velocities and density as in the standard model. Both sea-floor and interface between 1st layer and half-space are gently sloping with an inclination of 4.6° , while the thickness of 1st layer remains constant. As a result, water depth ranges from 6 m to 18 m over 150 m distance in the horizontal direction. A total of 7 shots were modelled with a 25 m source spacing (shot are numbered from left to right). Two different acquisition scenarios were tested:

- source and receiver at same and constant depth below the sea surface, for all shots (see Fig.6.1a). Receivers are placed at the right of the shot point.
- source and receiver at same depth but varying with shots, with a constant distance (3 m) of sources over the sea-floor (see Fig.6.1b) . Receivers array is always horizontal and placed at the right of the shot point.

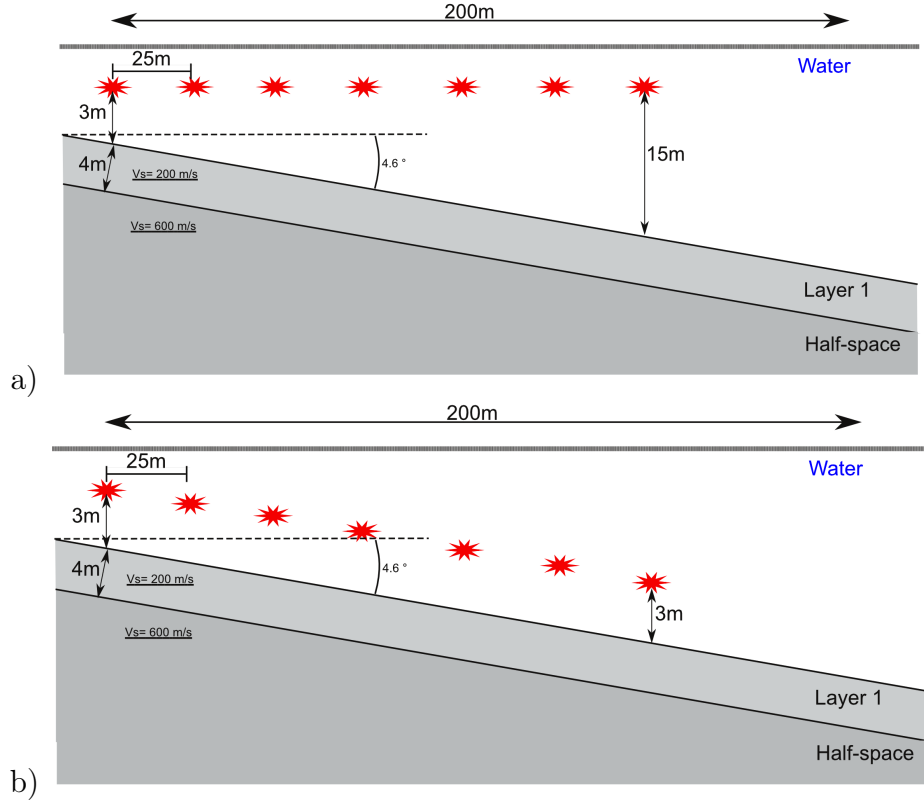


Figure 6.1: Representation (not in scale) of a laterally varying sea-bottom topography in the input model and two different acquisition strategies: source and receiver at constant depth (a) and source and receiver at variable depth (b)

6.3 Results

6.3.1 Source and receiver at constant depth

For each shot, a dispersion plot was produced. Auto-picked fundamental modes were then inverted to produce the 1D Shear wave velocity profile for a point referred to the middle of the spread. In Fig. 6.2 (phase-velocity/frequency) plots are shown for shot no. 1, 4 and 7. A strong degradation of the fundamental mode is noticed for increasing distance of source from the sea-floor. Picking is possible up to the fourth shot whilst for the following shots dispersive events are no longer recognisable. From our modeling we conclude that the maximum acceptable distance of the source from the sea-floor is around 9 m. For larger values, no information of the V_s variation with depth can be retrieved. As demonstrated by Allouche et al., (2011), only if the ratio h/λ (where h is the source height over the sea floor and λ is the dominant frequency in water) is small the source generated P-wave significantly converts to S-wave, giving rise to propagating Scholte waves along the sea-floor (*near field* condition).

This is confirmed by our modeling results: when the $h \geq 9$ m (meaning $h/\lambda \approx 0.25$) Scholte wave is no longer recognised in both seismograms and (v,f) plot. Contrarily, for lower h (up to a minimum of 3 m) Scholte waves have been always generated ($h/\lambda \approx 0.1$)

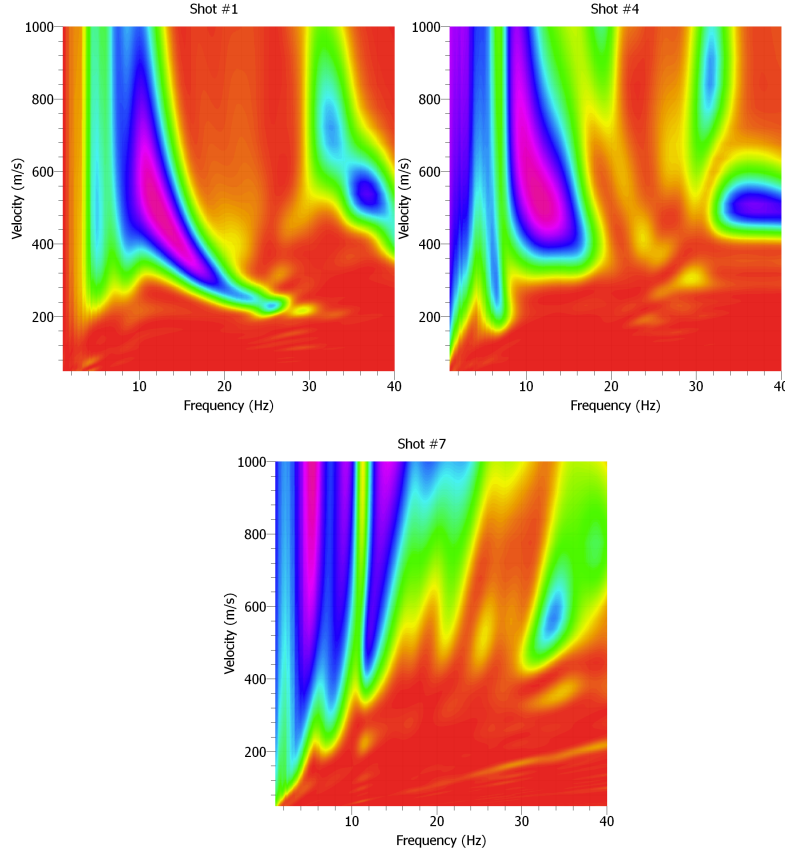


Figure 6.2: Dispersion plot for shot no. 1, 4 and 7 for the inclined sea-floor model with source and receivers at fixed depth below the sea-surface. A nearest offset of 10 m and 48 channels at 1 m spacings are used. Note for shot no. 4 how the source distance above sea-floor influences the quality, resolution and uncertainty of both fundamental mode and 1st higher mode. In shot no. 7 Scholte waves dispersive event are no longer recognisable.

In Fig. 6.3 the retrieved models after inversion are shown for the first four shots. We observe that for an increasing distance of the source from the sea-floor, both velocities of 1st layer and half-space are increasingly overestimated. This is likely due to the increasing travel path of the wavefield within the water layer before reaching the deployed receivers. On the other hand, the inferring of the depths of the boundary between the 1st layer and half-space seem to be less affected by the variation of source distance above the the sea-floor.

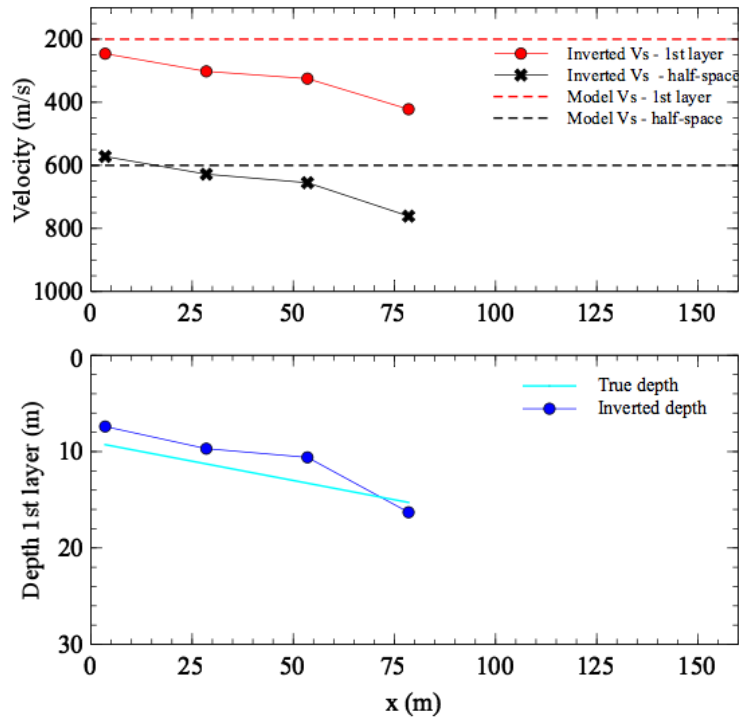


Figure 6.3: Inversion results for the first 4 shot positions for an inclined sea-floor with source and receivers at constant depth below the sea-surface.

6.3.2 Source and receiver at variable depth

Similarly to the previous case, for each of the seven shots a dispersion plot was produced. Sources distance from the sea-floor was kept constant at 3 m and receivers were (horizontally) deployed at the same depth of the source. In Fig. 6.4 (phase-velocity/frequency) plots are shown for shot no. 1, 4 and 7. Contrarily to the previous acquisition scenario, Scholte waves were recorded in all seven shots. As a result, the fundamental modes were always recognisable and possible to be picked.

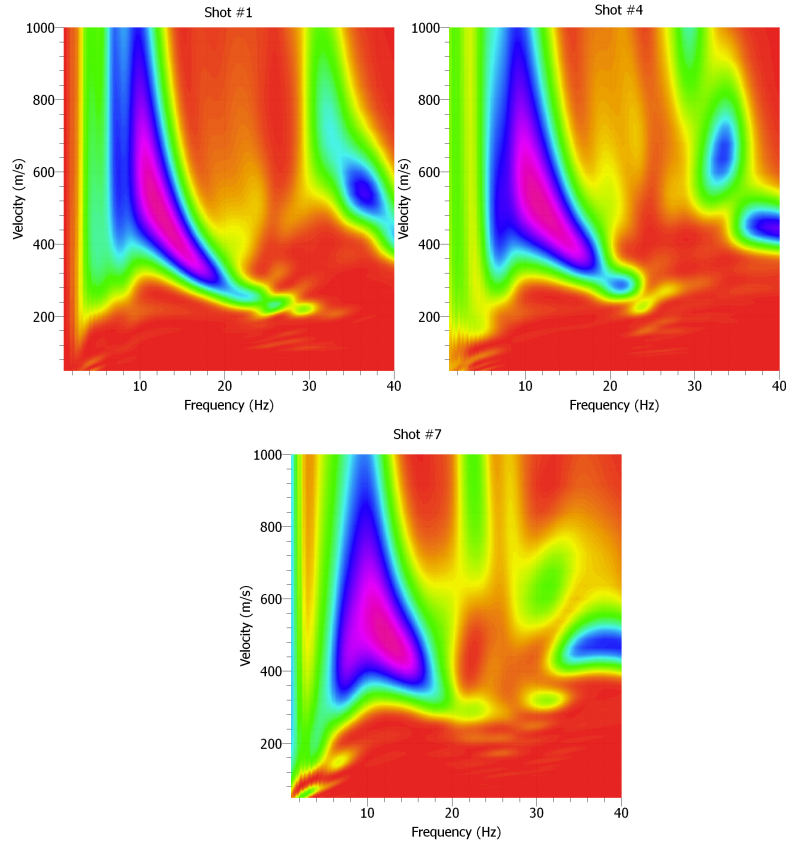


Figure 6.4: Dispersion plot for shot no. 1, 4 and 7 for the inclined sea-floor model. Source height over the sea-floor is constant (3 m) and receivers are deployed at the same depth as the source for each shot point. A nearest offset of 10 m and 48 channels at 1 m spacing are used.

Even though the distance of source from the sea-floor was constant for all shots, differences can be appreciated in the characteristics (mainly shape, while resolution is relatively the same in all cases) of the fundamental modes. For each shot point the only variable is total water depth, therefore those differences in the fundamental modes might be due to an increasing water layer along the profile. In Fig. 6.5 the inversion results are shown for each shot. Both V_s of the 1st layer and half-space as well as the depth of the interface between those are well inferred. Nevertheless, depth is in all cases slightly underestimated while V_s of the 1st layer is always overestimated. The reason for the higher V_s for the 1st layer can be the water layer between receivers cable and sea-floor that increased in thickness along the spread. It results that the converted P-wave from Scholte waves has to travel more in fluid (with high velocity) leading to an higher apparent velocity of Scholte waves. Most importantly, no particular trend in variation of V_s or depth can be noticed along the profile in the inversion results. It demonstrates that a varying total water layer thickness (that ranges from 6 m to 18 m over 150 m) for each shot point does

not affect the propagation of Scholte waves and their correct acquisition, leading to comparable inverted Vs profile.

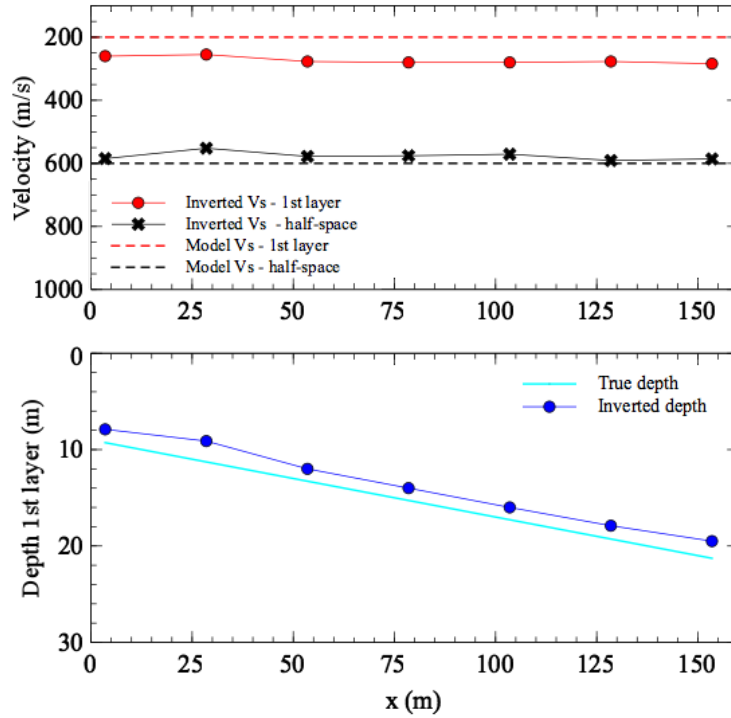


Figure 6.5: Inversion results for each of the seven shots along the profile.

It has been demonstrated that in case of a laterally varying sea-floor, it is necessary to adjust source and receivers depth according to the sea-floor topography in order to correctly acquire Scholte waves. Otherwise, if source and receivers are placed at constant depth, Scholte waves would be generated and properly recorded only up to certain maximum distance of the source from the sea-floor (around 9 m). In addition, for an increasing distance (but still within the maximum of 9 m), the inverted Vs profile would suffer of a strong error due to the relevant overestimation of shear-wave velocities.

Chapter 7

Testing 1D inversion assumption

7.1 Motivation

In order to retrieve the shear wave velocity profile of the subsurface, the fundamental mode of dispersion is inverted in a one-dimensional approach. It means that the subsurface is assumed as horizontally layered: S-wave velocity, P-wave velocity and density can only vary with depth and therefore lateral changes of those properties are neglected. For a certain shot, the inferred V_s profile is referred to the middle-point of the entire spread.

Lateral changes in properties are obviously present in the subsurface and it is expected that those can have an influence on surface waves propagation along the receivers spread. As a results, a single inverted 1D shear velocity profile averages all lateral inhomogeneity encountered along the spread. When acquiring surface waves along a certain profile by multiple shots, an obvious lack in lateral resolution is experienced. Moreover, each of the V_s profiles is affected by an additional uncertainty caused by the influence of lateral inhomogeneity.

Currently, a 2D approach to the inversion problem for surface waves has not yet been developed. Consequently, when acquiring surface wave, a suitable strategy should be adopted in order to reduce the contribution of lateral inhomogeneity along the receiver array. The common recommendation consists of keeping the receiver spread as short as possible so that less lateral variations are encountered and averaged in a single V_s profile. That is the reason why in Chapter 4, when modeling four different channel numbers (24-48-72-96), the optimal value (48 channels) has been chosen as the best trade-off between results from the inversion and shortness of the spread length.

In the following section, the 1D inversion assumption will be tested. Our optimal acquisition set-up will be used in case of two different input models comprising lateral

inhomogeneity of subsurface properties.

7.2 Modeling

Inclined interface

The standard input model has been slightly modified as shown in Fig.7.1. The interface between 1st layer and the underlying half-space has been inclined of 4.6° . Consequently, the 1st layer has a thickness ranging from 4 m to 20 m over 200 m. In total 9 shots with 25 meters spacing have been modeled (numbered from left to right in Fig.7.1). Regarding the acquisition parameters: a nearest offset of 10 m and 48 channels at 1 m spacing are used. The receivers spread length is therefore 47 m.

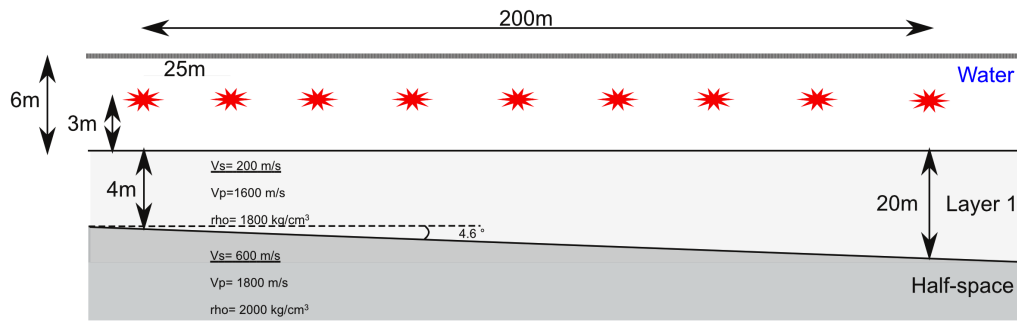


Figure 7.1: Input model with a gently inclined interface used for testing the 1D inversion approach. Receivers are placed at the right relative to the shot points.

It is worth noticing that, given the increasing thickness (up to 20 m) of the first layer, it would be possible to define the maximum depth at which the interface between 1st layer and half-space can be recognised, giving an idea of the maximum depth of investigation using Scholte waves.

Channel in-fill structure

A more complicated structure has been implemented in the standard model including a channel in-fill structure, as shown in Fig.7.2. The interface between 1st layer and half-space has a channel structure, 100 m wide with a maximum depth of 6 m. The geometry is symmetric and both flanks have an inclination of around 13.5° . A total of 9 shots have been modeled with a shot spacing of 15 m along an overall distance of 120 m. As in the case above, source and receiver are always placed at 3 m above the sea-floor. Acquisition parameters are the same as the previous model for a total spread length of 47 m.

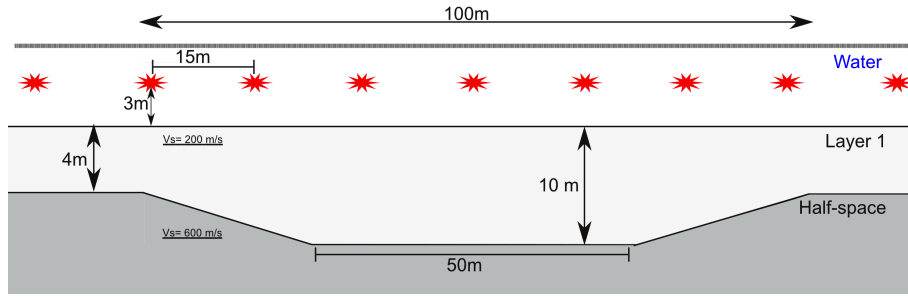


Figure 7.2: Input model with a channel in-fill structure. Shots are numbered from left to right.

The input model shows a very high complexity and has been properly chosen to test the effective lateral resolving capabilities of a Scholte waves acquisition with a 1D inversion scheme. Note that, contrarily to the inclined interface case, steeper boundaries are present (flanks) in the channel in-fill structure. In each of the shots, the 47 m long receivers spread always records Scholte waves travelling on a interface with varying depth and inclination. As a consequence the averaging results in the inverted Vs profile for each of the midpoint is expected to be rather severe. Since the model structure is symmetric, a possible difference in results (in dispersion plots and inversion results) depending on the up-slope or down-slope travel path of Scholte waves could be appreciated.

7.3 Results

Inclined interface

For the inclined interface model, dispersion plots have been produced for each of the 9 shots. In Fig. 7.3 the dispersion plots referred to shot no. 1, 4, 7 and 9 are shown. In the (v,f) plots of the last three shots (shot no. 7, 8 and 9), the dispersive events referred to Scholte waves are no longer recognised; from this we conclude that the maximum depth of investigation (measured from the receiver cable) using Scholte waves could be around 20 m for the chosen model of subsurface and acquisition set-up. The fundamental modes have been picked and inverted in order to obtain the Vs profiles (referred to the middle-point of the receiver spread).

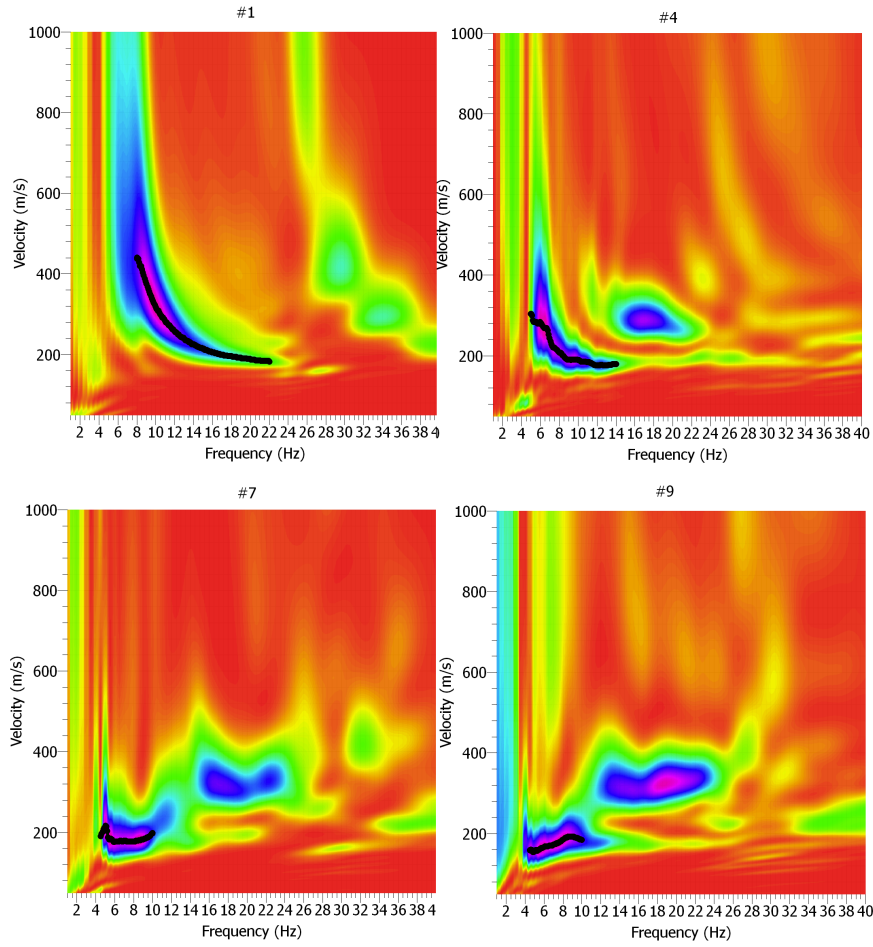


Figure 7.3: Dispersion plots for shot no. 1, 4, 7 and 9 for an inclined interface model. A nearest offset of 10 m and 48 channels at 1 m spacing were used.

In Fig. 7.4 the inversion results are presented for the first 6 shots. For shot no. 7, 8, and 9 the full V_s profile could not be retrieved due to a scarce penetration of dispersive Scholte waves; the shear wave velocity of the half-space could not be inferred due to its negligible contribution on Scholte waves.

Considering the first 6 shots, the slight lateral inhomogeneity implemented in the model appears to have a strong influence in the inversion results. As a result of averaging of the subsurface properties along the 47 m long spread, the shear wave velocity of the half-space is increasingly underestimated as the 1st layer becomes thicker to the right of the model and the sensitivity of Scholte waves decreases with increasing depth. The contribution of the 1st layer becomes more dominant moving along the profile, leading to an erroneous estimation of the V_s of the underlying half-space. From shot no. 3 onwards, also the determination of depth becomes increasingly erroneous.

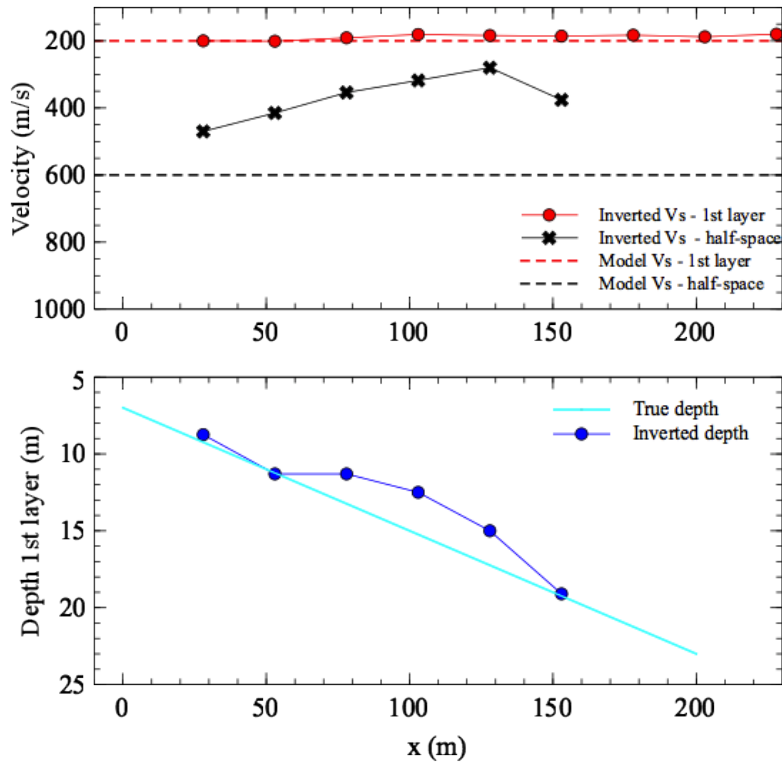


Figure 7.4: Inversion results for a dipping interface between 1st layer and half-space. In shot no 7,8 and 9 no information about Vs variation with depth can be obtained, due to scarce penetration of Scholte waves.

For our acquisition parameters, it can be concluded that the maximum depth at which a certain boundary can be recognised is roughly 10 m and for this case the averaging effect of lateral properties can be still acceptable. Moreover this result confirms what stated by Stokoe et al. (1994) for the MASW case on land: the maximum depth of investigation is generally equal to the nearest offset ($x_1=10$ m in our case).

Channel in-fill structure

For the channel in-fill model, dispersion plots have been produced, for each of the 9 shots. In Fig. 7.5 shot no. 1, 2, 5 and 7 are shown as they are the most representative and interesting to be considered. The presence of a such channel structure and the resulting strong lateral variation has a severe impact on shape and resolution of the fundamental mode. As expected, especially when the spread midpoint is located on one of the two flanks (shot no. 2 and 7), a dramatic decrease in sharpness of the fundamental mode is shown. In this case, picking is rather difficult and prone to uncertainty. On the contrary, when the midpoint is located on the bottom of the

channel or out of it (where lateral variation are less prominent), the dispersion plots show an better resolution (shot no. 1 and 5).

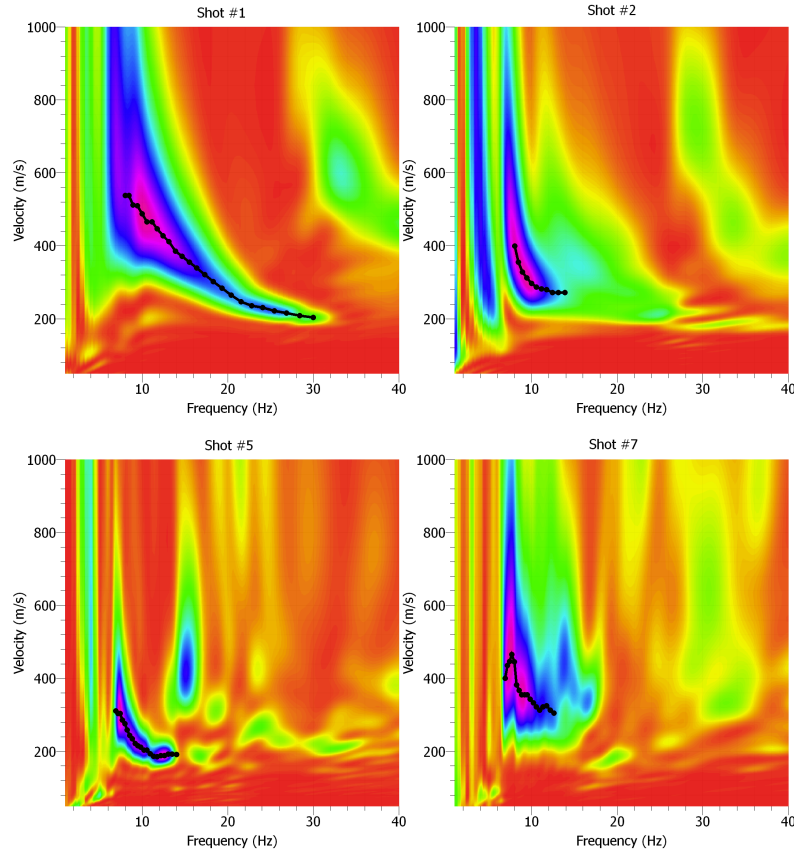


Figure 7.5: Dispersion plots for shot no. 1, 2, 5 and 7. Shot no. 2 and 7 are located over the strongly inclined channel flanks while shot no. 5 and 7 are located over flat interfaces, see Fig. 7.2.

In Fig. 7.6 the inversion results are shown for each of the shot along the profile. It is not surprising that the worst inversion results are obtained for shot no. 2 and 7. As already stated, for these case the midpoint lies on the 13° inclined flanks. Therefore, the encountered lateral variation of properties is maximum. Depth is strongly overestimated in both cases as well as the velocity of the half-space in shot no. 2.

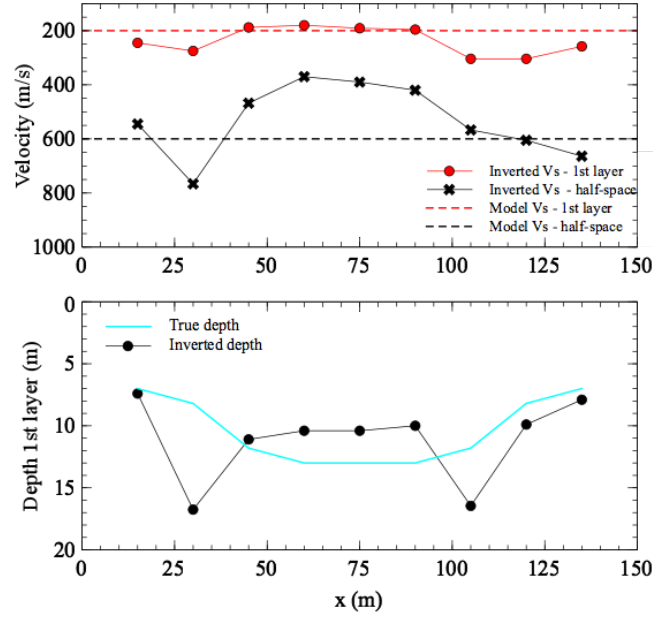


Figure 7.6: Inversion results for each of the 9 shots in case of a channel structure. Each Vs profile is referred to the midpoint of the spread. Note the strong error in velocity and depth determination in case of a strong lateral inhomogeneity, i.e. channel flanks (shot no. 2 and 7).

For shot no. 3, 4, 5 and 6, corresponding to the bottom of the channel structure, the determination of the velocity of the half-space is affected by a strong underestimation. This effect has been already observed in the case of a dipping interface. As the 1st layer becomes thicker (and the interface is at a distance >10 m from the receiver cable), the contribution to propagation of Scholte wave velocity of the underlying half-space becomes less prominent. Therefore, when inverting the fundamental modes, the Vs of the half-space is strongly underestimated (up to 33%). Apparently an up-slope or down-slope direction of travelling Scholte waves does not make any relevant difference. In both cases, a strong lateral variation in properties is encountered with a strong effect in the inversion results for both velocity and depth of the interface determination.

Concluding, it has been demonstrated that the 1D inversion assumption in the inversion scheme can lead to relevant errors in the inferred Vs profile when (even slight) lateral heterogeneity are present in the subsurface, even when using the shortest possible receiver spread. As long as a 2D inversion scheme is not developed, it should be kept in mind that all inverted Vs profile can be rather uncertain and erroneous due to the averaging effect of lateral heterogeneity along the receiver spread.

Chapter 8

Discussion

The determination of the optimal acquisition set-up has been possible by modeling Scholte waves propagation in case of a simple 1D model. Several acquisition set-ups have been tested varying *nearest offset* (x_1), *receiver spread length* (x) and *receiver spacing* (dx).

An acquisition set up with $x_1=10$, $x=47$ m (48 channel) and $\Delta x=1$ m has been demonstrated to be optimal when acquiring Scholte waves in two, rather different, geological conditions. Using this acquisition parameters, a good resolution of the fundamental mode is assured and reliable inversion results are inferred. Nevertheless only a simple 1D model comprising one layer and underlying half-space has been used. The acquisition set-up above should be tested also in case of a 1D multilayering (possibly including shear wave velocities inversion). Those are in fact the scenario mostly close to reality where also the higher modes, as well as the fundamental one, can have a strong relevance for the determination of a reliable Vs profile.

Contrarily to the land case, the acquisition of Scholte waves is affected by several limitation; commonly those are acquired using a streamer towed behind a vessel and are generated by air-guns. This means that parameters like receiver spacing are fixed and cannot be varied according to the needs; the possibility of variation of nearest-offset is more limited compared to the on land case. Source and receivers are horizontally placed at a certain distance from the sea-floor: it means that the water layer in between might have an effect as well as the variation of topography of the sea-floor (that could be "followed" within a certain limit by varying source and receivers position). In order to properly record Scholte waves, the proper acquisition set-up must be chosen. But, given the obvious limitation reported above, the optimal acquisition strategy and parameters should be feasible to most of the cases that can be encountered in a shallow marine environment. A solution for that would be the usage of a long streamer comprising 48 to 96 channels with spacing variable

between 1 m and 2 m (in order to avoid aliasing of higher modes). Afterwards, in the processing phase, it can be decided to select part of the entire shot gather (or channels with a certain step) in order to "simulate" several acquisition set ups. Giving an idea, according to the previous knowledge of the site and/or the aim of the survey it can be decided to prefer a rather high vertical penetration over a poor lateral resolution by having a long nearest offset and receiver spread.

Another main issue when acquiring Scholte waves would consists in the requirement for the source (and receivers) to be as close as possible to sea-floor, mostly within 9 m according to our modeling results. This would require a continuous adjustment of source receivers depth according to the sea-floor topography. The effective applicability of this procedure should be verified. Moreover, such a short distance of a powerful, low frequency, pressure source could cause a relevant threat for the marine fauna in the vicinity of the water-sediment interface.

Last but not least is the issue related to the 1D assumption used for the inversion of surface waves, both for land and marine case. Our modeling results showed the strong influence of lateral heterogeneities when inferring a Vs profile even for a gently dipping interface and with a rather short receiver spread (47 m). As long as a 2D inversion algorithm is not developed, this inversion-related problem has to be taken into account in the acquisition phase since any inferred Vs profile represent an averaging of subsurface properties along the entire length of the spread, leading to relevant uncertainty of the inferred Vs profile, that can be decreased only using a short receiver spread.

Chapter 9

Conclusion

The aim of this thesis was the determination of the optimal acquisition set-up for Scholte waves acquisition in a shallow water environment. A FD, elastic scheme was used for the modeling of Scholte waves propagation in case of a simple 1D model. Several acquisition set-ups have been tested varying *nearest offset* (x_1), *receiver spread length* (x) and *receiver spacing* (Δx).

Regarding the *nearest offset*, it has been demonstrated that a value of x_1 ranging from 0 m to 5 m lead to a severe near offset effects that also results in a less resolved fundamental mode in the (v,f) plot. Moreover, both high (> 60 m) and low values (0-5 m) of nearest offset have a detrimental effect on the resolution of higher modes (that could be used is a multi-modal inversion approach). Investigating the inversion results, it has been noticed that the optimal values for x_1 is around 10 m, as predicted applying the formula by Zhang et., (2004). Contrarily, according to the rule of thumb proposed by Stokoe et al., (1994) the optimal value for x_1 would have been at least 27 m; nevertheless, using 30 m as nearest offset, a relevant error is noticed when determining both velocities and depth; it suggests that this rule should be carefully used. For low velocities of propagation, near offset effect was less severe and the value $x_1=10$ m has been confirmed to be feasible also in this case.

Four different values of *receiver spacing* have been tested, from a minimum value of 0.5 m to a maximum of 4 m. In our modeling results, even for the coarser spatial sampling the fundamental mode was not affected by spatial aliasing. Only the higher modes, due to their higher frequency content, lied in the spatially aliased region of the dispersion plot when $\Delta x = 4$ m is used. To appreciate the (possible) effect of spatial aliasing on Scholte waves, the minimum shear wave velocity has been decreased of 50%. Surprisingly it has been observed that in this case the maximum frequency of Scholte waves was around 13 Hz (compared to 30 Hz of the previous

case). As a consequence, even decreasing the minimum velocity of propagation, the minimum wavelength remained comparable to that of the standard model. The fundamental mode still lied in the un-aliased region in the dispersion plot even for a $\Delta x = 4$ m. Again, only the 1st higher mode partly falls in the spatially aliased region. It is expected that a minimum shear wave velocity as low as 50 m/s would lead to similar results: the Scholte waves frequency band would be again shifted towards even lower frequencies avoiding spatial aliasing. There are reasons to believe that a receiver spacing up to 2 m would be sufficiently short to avoid spatial aliasing also when poorly consolidated, low velocity materials are encountered in the subsurface.

The last parameter tested was the *spread length* (varying the channel number from 24 up to 96, accordingly). When 24 channels were used ($x=23$ m, $\Delta x=1$ m and $x_1 = 10m$), a strong worsening in resolution of the fundamental mode in the (v,f) plot was noticed. In addition, the picked fundamental mode showed a rather dissimilar shape from those obtained with 48, 72 and 96 channels. Such difference has been explained by the fact that a spread length of 23 m is not sufficient for different traveling phases to separate along the receivers array. Consequently, the fundamental mode is poorly resolved due to an excessive overlapping of phases in time and space. As expected, such effect has detrimental consequences on the inversion result that in fact showed erroneous results especially for depth determination. When using 48 channel ($x=47$ m), the improvement in resolution is considerable and roughly comparable to that obtained with longer spread lengths. In case of lower Vs (decreased by 50 %) it has been shown that 24 channels appear to be sufficient to avoid an overlapping of events as they need a shorter travel path for separation to occur.

In conclusion, given that sediments in shallow marine environment might have a maximum Vs as high as the ones implemented in the first standard model (200 m/s and 600 m/s for the 1st layer and half-space, respectively), a total spread length of 47 m with 48 channel at 1 m spacing would assure an optimal acquisition of Scholte waves in most of the geological condition.

As already stated above, another major issue when acquiring Scholte wave consists in the presence of a non horizontal sea floor. It has been investigated whether it is better to adjust, according to the sea-floor variation, source and receiver positions or maintaining those at constant depth. When using source and receivers at constant depth, the determination of Vs of both 1st layer and half-space was affected by a strong overestimation. The reason for that has to be found in the thickening water layer between sea-bed and receiver spread. It causes converted P-wave component of Scholte waves to travel more in the (high velocity) fluid, leading to a

higher apparent shear wave velocity. Better results were obtained when the position of sources is maintained constant over the the sea-floor with receivers at the same depth as the source also when water depth was maximum (18 m). The inversion results were mostly equivalent for each of the shots demonstrating that a variation of water layer thickness does not have an influence over Scholte wave acquisition as long as the source and receivers "follows" the topography. As demonstrated by Allouche et al., (2011) only if the ratio h/λ (where h is the source height over the sea floor and λ is the dominant frequency in water) is small the source generated P-wave significantly converts to S-wave, giving rise to propagating Scholte waves along the sea-floor (*near field* condition).

To study the influence of the 1D assumption in the inversion, the standard input model have been modified implementing a gently dipping interface between 1st layer and half-space. The determination of the Vs of the half-space was affected by strong underestimation (up to 30%), increasing for deeper depth of the interface.

A model with increased complexity has been implemented. Consisting of a channel in-fill structure, it gave the possibility to test the influence of stronger inclined interfaces. As expected, in this case the underestimation of the half-space Vs was even more severe especially where the 1st layer was thicker. When trying to image the depth of the channel flanks, a relevant error was encountered. Summing up, when dealing with real data, the inverted 1D Vs profile represent an average of subsurface properties over the entire length of the receiver array. A 2D inversion scheme would solve this issue but it has not developed for dispersive surface waves yet.

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