Marine guided-waves: Applications and filtering using physical modeling data

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SUMMARY

Guided seismic waves in the water column can be energetic events, especially at shallow depths. This paper investigates guided-wave properties, their use, and filtering with the help of physical modeling experiments. We investigate how different parameters (water depth, density of the seafloor, and both P-wave and shear-wave velocity of the seafloor) affect the guided-wave properties. A number of physical modeling experiments, at the ultrasonic surveying facilities of Allied Geophysical Laboratories (AGL), are conducted. The physical modeling data fit theoretical calculations very well. For a horizontal or slightly dipping seafloor, extracting the shear-wave velocity from guided-waves with a curve-fitting method is accurately achieved. Both theoretical analysis and physical modeling indicate that guided-waves obscure reflection data, which makes removing guided-waves necessary. Because the normal modes of guided-waves are less obvious in the $f-k$ domain, we design a *dispersion curve filter* in the phase velocity and frequency domain ($v-f$ domain). The filter is tested on the physical modeling data. The results show enhanced reflections and attenuated guided-waves, which can benefit further processing and interpretation.

INTRODUCTION

Guided-waves are commonly found in seismic data from shallow water environments. With their relatively strong amplitudes, they can obscure the reflections from deeper targets. Note that these guided-waves interact with the seabed and therefore are sensitive to the shear-wave velocity of the subsurface material. (Klein et al., 2005). So, studying guided-waves may also benefit ocean-bottom seismic processing and interpretation.

In this paper, we first study the influence of different water depth and physical properties (density, P-wave and shear-wave velocity) in the marine environment on the dispersive spectra. Then, similar to the MASW method developed by Park et al. (1998), we extract some of the physical properties from the dispersive spectrum of the guided-waves. Finally, we design a *dispersion curve filter* in the phase velocity and frequency domain to attenuate the guided-waves.

DISPERSION PROPERTIES

The dispersion equation of guided-waves in a layered model was first given by Pekeris (1945) with the assumption that all layers are liquid. Press and Ewing (1950) extended Pekeris' development to an elastic sea-bottom. The dispersive equation is:

$$\tan\left[k_n H\sqrt{c^2/v_1^2-1}-(m-1)\pi\right]=\frac{\rho_2}{\rho_1}\frac{\beta_2^4}{c^4}\frac{\sqrt{c^2/v_1^2-1}}{\sqrt{1-c^2/\alpha_2^2}} \cdot\left[4\sqrt{1-c^2/\alpha_2^2}\sqrt{1-c^2/\beta_2^2}-(2-c^2/\beta_2^2)^2\right], \quad (1)$$

where H is the water column thickness, ρ_1 and ρ_2 are the density of water and seafloor, respectively, k_n is the wavenumber of nth mode, v_1 is velocity in water, α_2 is the P wave velocity of seafloor, β_2 is the S wave velocity of the seafloor, c is the guided-wave phase velocity.

Adjusting different parameters in Equation 1 yields how sensitive the dispersion curves are to these parameters, *i.e.* Vp/Vs, Vs, ρ, h. The results are shown in Figure 1. Only one parameter is changed, others remain the same: Water depth is 100 m, sound velocity in the water is 1500 m/s, P-wave velocity of the seafloor is 6300 m/s, Shear-wave velocity of the seafloor is 3300 m/s, density of the seafloor is 2.7 kg/m^3. Only the first mode is plotted.

We can see Vp and density do not affect the dispersion curves strongly, so they can be estimated from shot gathers or other empirical equations and considered as known factors. The depth of water does affect the dispersion curves, but it can be determined accurately from bathymetric surveys. So, we are left with one variable, the shear-wave velocity of seafloor, to determine from the dispersion curves of guided-waves.

PHYSICAL MODELING

Figure 2 shows the physical modeling system that we used at Allied Geophysical Lab, University of Houston. We employed an aluminum block as the hard sea floor. The P-wave and S-wave velocity and density of aluminum block are 6200 m/s, 3258 m/s, and 2.7 kg/m^3, respectively, which are similar to basalt ($Vp = 6300$ m/s, $Vs = 3200$ m/s, density=2.4 kg/m^3). The survey design of the experiment is shown in Figure 3. The central frequency we used is then 30 Hz. The experiment was designed in 2D cylindrical coordinates. The source, receiver and the apex are in the same plane. Different water depths are for 45 m to 100 m are surveyed.

The shot gathers are shown in Figure 4. The classic guided-wave fans are observed in both shot gathers. The data show guided-waves have very strong amplitudes and obscure the reflections from the water bottom. The dispersion curves of guided-waves can be nicely identified in the phase velocity-frequency domain ($v-f$ domain) with a wavefield transform (McMechan and Yedlin, 1981; Park et al., 1998). Figure 5 shows the dispersion curves of guided-waves (data from Figure 4) using the method of Park et al. (1998). In physical mdoeling, we know every parameter precisely. Therefor we can calculate the theoretical dispersive curves with Equation 1 and then overlap the theoretical curves with the dispersive

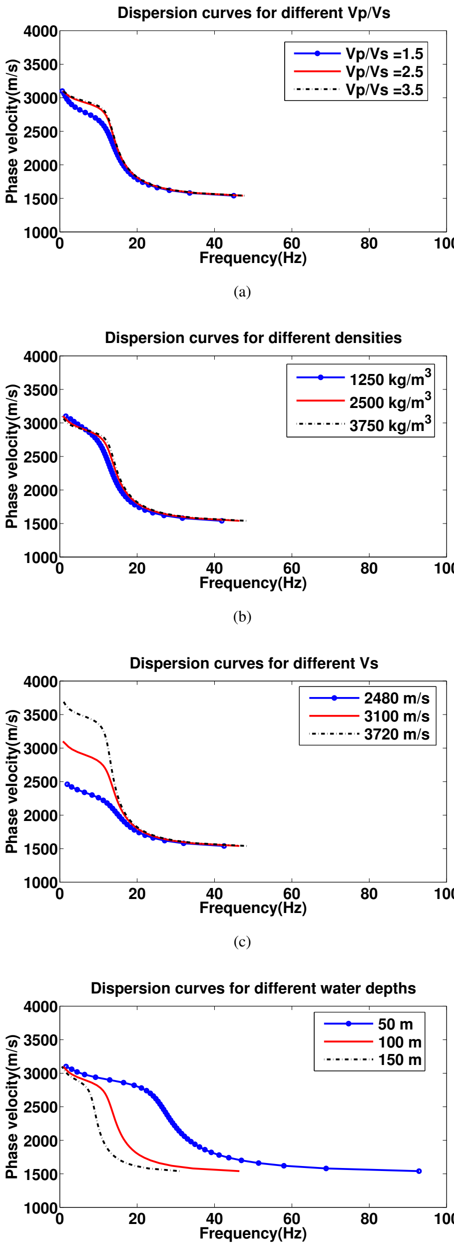


Figure 1: The sensitivities of dispersion curve on different parameters, *i.e.* Vp/Vs value, ρ, Vs, h. Only the first mode is plotted here. (a) Vp/Vs is changed from 1.5 to 3.5. (b) ρ is adjusted from 1250 kg/m^3 to 3750 kg/m^3. (c) Vs is changed from 2480 m/s to 3720 m/s. (d) Water depth is changed from 45 m to 150 m.

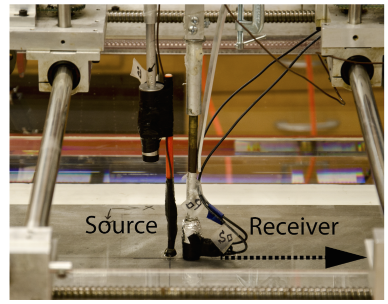


Figure 2: The physical modeling system used for marine guided-waves modeling. The gantry, source and receiver, plus model are shown. The source is placed in the center of the block and receiver is moved away from the source. The dashed line arrow indicates the moving direction of the receiver.

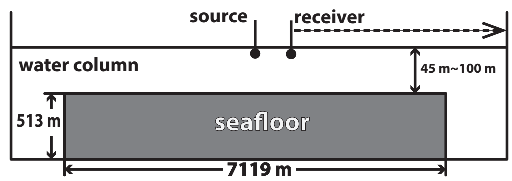


Figure 3: Physical modeling geometry. Offset range: 200∼3500 m, Receiver interval: 10 m. Two different water depths are simulated: 45 m and 100 m. The dashed line arrow indicates the moving direction of the receiver.

spectrum of physical modeling data. The theoretical calculation fits the experimental data very well. The dispersion curves of different water depths indicate that water depth not only effects the shape of certain mode in dispersive curve, but also effects the interval of different modes. Given a certain frequency range, the more shallow the water column, the fewer modes received.

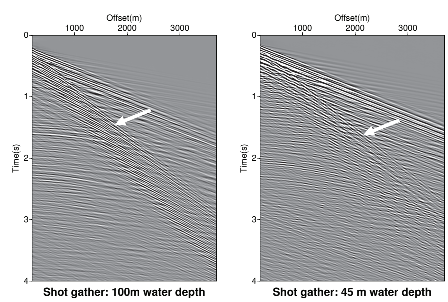
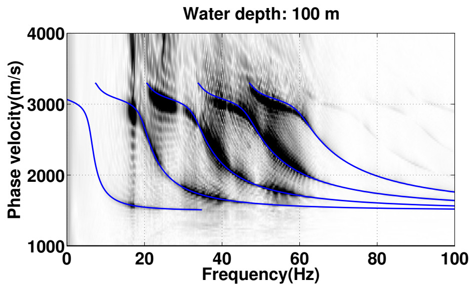


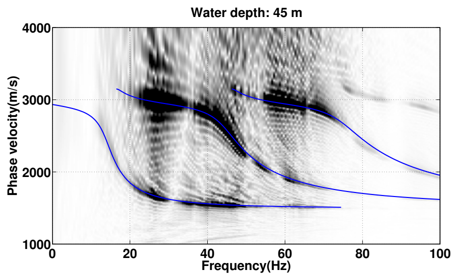
Figure 4: Shot gathers from physical modeling data. Left: 100 m water depth. Right: 45 m water depth. The arrows indicate the guided-waves.

EXTRACTING SHEAR-WAVE VELOCITY

We discuss the possibility of extracting shear-wave velocity from the guided-waves. As shown previously, Vp, ρ, and wa-



(a)



(b)

Figure 5: Dispersion plots for different water depths overlying a flat seafloor. The blue curves are the theoretical calculation. (a) 100 m water depth. (b) 45 m water depth.

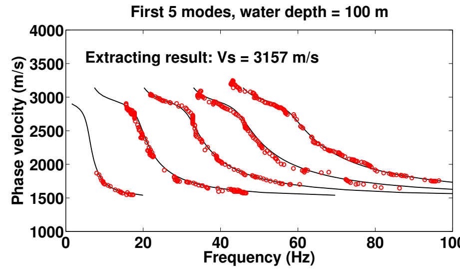
ter depth can be considered as know factors, thus shear-wave velocity is the only one unknown parameter in the dispersion equation. Extracting the shear-wave velocity of seafloor from guided-waves can be cast as least-squares problem by minimizing the residual between the dispersion curves from the data and a predicted dispersion curves from the shear-wave velocity (Levenberg, 1944; Marquardt, 1963). We solve this problem iteratively by finding Vs such that:

$$\min_{V_s} \| F(V_s, c^{data}) - F^{data} \|_2^2 = \min_{V_s} \sum_i \left(F(V_s, c^{data_i}) - F^{data_i} \right)^2, \quad (2)$$

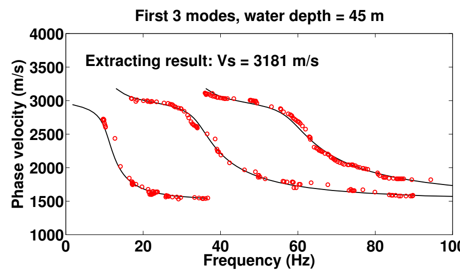
where c^{data} phase velocity corresponding to certain frequency from the data, F^{data} is the observed dispersion curves, and $F(V_s, c^{data})$ is the predict dispersion curves from c^{data} and estimated V_s.

The Jacobian matrix is calculated with the finite difference method (Gavin, 2011). The Levenberg-Marquardt method can solves this problem efficiently given a good estimated initial shear-wave velocity. However, the dispersive spectra can sometimes be noisy, making the estimation of initial shear-wave velocity less accurate. To achieve a more rapid convergence, we use the trust-region-reflective method (Coleman and Li, 1994, 1996a,b), which is similar to Levenberg-Marquardt method, except that the bound is updated from iteration to iteration (Yuan, 2000).

Figure 6 is the cure-fitting results with the data from Figure 5. In Figure 6(a) (100 m water depth), we picked first five modes as input data. In Figure 6(b) (45 m water depth), only first three modes are picked because of the weak amplitude in higher modes.



(a)



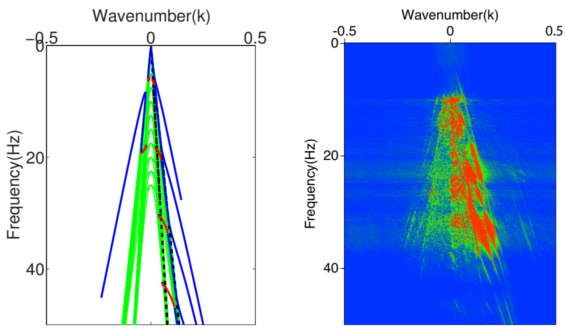
(b)

Figure 6: Curve-fitting and shear-wave velocity extraction result. (a) 100 m water depth. (b) 45 m water depth. The dots are picked from physical modeling data from two experiments with different water depths. The solid curves are final calculated dispersion curves.

The lab measurement of shear-wave velocity of seafloor (from direct transmission measurements) is $Vs = 3158 \pm 56\, m/s$. The curve-fitting of physical modeling data yield 3157 m/s (100 m water depth) and 3181 m/s (50 m water depth). Considering the error of the lab measurement, the extracted result from the guided-waves is reasonable.

DISPERSION CURVE FILTER

From the above discussion, we can see that the normal modes of the guided-waves have significant influence on marine seismic data. After parameters estimation from the guided-waves, their removal is the goal. The $f-k$ filter is a workhorse in attenuating dipping noise. To identify the guided-wave signature in the $f-k$ spectrum, we transform the theoretical calculation of dispersion curves of only the guided-waves (only the normal modes) and the full spectrum (both the normal modes and the leaky modes). Figure 7(a) shows the results. In the low frequency range, all events overlaps together. The difference between the normal mode spectrum and the full spectrum is small. Some of the normal modes even overlap with the leaky modes. As mentioned before, the real part of the leaky modes is the Scholte waves. It is difficult to separate the guided-waves in the $f-k$ spectrum from the Scholte waves. The converted reflections and refractions cut through the normal modes and leaky modes. So, for multicomponent seismic data, attenuating guided-waves without damaging converted wave signal in $f-k$ domain would be very challenging. Transferring our physical modeling data (100 m water depth) into $f-k$ domain (the left figure in Figure 7(b)), with the blurring effect in the real data, we find the guided-waves, different reflections, and the refractions superpose, which makes the isolation of guided-waves in $f-k$ domain even more difficult.



(a) (b)

Figure 7: Transferring the dispersion curves into the $f-k$ domain. (a) the normal modes and leaky modes, blue curves are normal modes, red curves are leaky modes, black dashed lines are $P-$wave and converted wave refractions, green curves are $P-$wave and converted wave reflections. (b) $f-k$ spectrum of physical modeling data (100 m water depth).

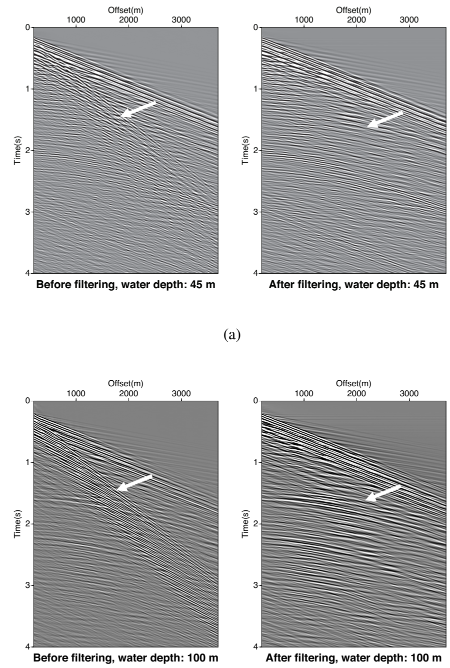
Because the $f-k$ filter is unlikely be completely satisfactory, we seek a new way to filter. The normal modes and leaky modes are well separated in the $v-f$ domain (Pekeris, 1945; Press and Ewing, 1950). Moreover, different modes of normal modes are also well separated. We design a filter in the $v-f$ domain. McMechan and Yedlin (1981) developed a method of transferring the shot gather into slowness-frequency domain ($p-\omega$). Their method requires long offsets and wide incident angles, which is appropriate for our marine case.

According to previous section, all the parameters can be considered as known (Vp, ρ, h) or well estimated (Vs). So, calculating the dispersion curves of guided-waves and masking data along these curves in the $v-f$ domain with these curves will largely reject the guided-waves while minimizing attenuation of other events.

To test our method, we applied this masking filter on our physical modeling data set, both 100 m and 45 m water depth (Figure 8). No gain enhancement is applied to the data. As we can see, the guided-waves (indicated by the arrow) are attenuated quite well. Because the guided-waves contain considerable energy in the shot gather, after applying the dispersion curve filter, the energy of reflection and refraction become more distinct.

CONCLUSIONS

Guided-waves can obscure reflections in marine seismic data, but they carry information about the seafloor. These guided-waves are well observed in physical modeling data. The dispersion curves from the physical modeling data match theoretical calculations very well. The shape of the guided-wave dispersion curve is largely determined by the shear-wave velocity of the seafloor and is not sensitive to other physical parameters. We are able to extract the shear-wave velocity of the seafloor from the guided-waves with a least-square based curve-fitting method. Existing filtering techniques may have difficulty separating the normal modes energy from other events. We developed a dispersion curve filter. The filter is tested on two physical modeling data with different water depths. The results show that this dispersion curve filter works very well and may benefit further processing and interpretation.



(a)

(b)

Figure 8: Comparison between original (left) and filtered (right) shot gathers. (a) 45 m water depth. (b) 100 m water depth.

ACKNOWLEDGMENTS

We would like to thank Anoop William of the Allied Geophysical Laboratories (AGL) at University of Houston who provided us with substantial assistance with the experiments. Dr. Bob WiIey also with AGL helped with software development. We are grateful to Geokinetics, Houston for generously supporting this project. We are also grateful to Dr. Soumya Roy formerly of the University of Houston for inspiring discussions.

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