Geol 483.3

Lab project #3 – Analysis of a shallow surface-wave dataset (MASW)

In this lab project, you will:

1) Look at high-resolution surface wave data collected during the field school in 2021;
2) Measure the phase-velocity dispersion for surface waves generated by hammer strikes;
3) Invert these velocity dispersion data for a layered S-wave velocity model.

The seismic line was collected by using 72 channels of our 96-channel seismograph over an about 20-m long line on top of the upper walkway on the riverbank slope near Saskatchewan crescent in Saskatoon. The line was fairly straight, and the geophones were placed at 0.3-m spacings. For seismic sources, we used a two-pound hand hammer.

The target of this survey consists of shallow layering to about 10-20 m depth, with the most interesting structure as shallow as 1-2 meters. We will investigate this layering by using the Multichannel Analysis of Surface Waves (MASW).

In MASW, a line of geophone is placed at spacings shorter than the Nyquist aliasing limit $\Delta x_{\text{Nyquist}} = \frac{\lambda_{\min}}{2}$, where $\lambda_{\min} = \frac{V_{\min}}{f_{\max}}$ is the shortest wavelength expected in the data, $V_{\min}$ is the lowest surface wave velocity and $f_{\max}$ is the highest frequency expected in the data. To resolve shallow structures, you would expect $V_{\min}$ as low as 0.1 km/s (0.1 m/ms) and would need frequencies $f_{\max}$ as large as possible. Similarly, the length of the geophone spread L determines that longest wavelength that can be imaged by the geophone array: $L = \frac{\lambda_{\max}}{2}$, and $\lambda_{\max}$ is related to the largest velocity $V_{\max}$ and lowest frequency f_{inin}.

The idea of MASW technique consists in detecting coherent harmonic waves within the recorded wavefield. These waves are usually produced by the source (hammer), but background noise such as traffic or microtremors can also be used. A harmonic wave at angular frequency $\omega = 2\pi f$ and velocity V has the following dependence on the distance x and time t, which we discussed many times in class

$$u_n(x,t) = A_n e^{-i\omega\left(t - \frac{x}{V_n}\right)}, \quad (1)$$

where A_n is the amplitude and n is the wave mode number. Within a layered structure, there exist depth and by different values of velocities V_n. The mode with the lowest propagation velocity is called the <u>fundamental mode</u> and denoted by $n = 0$ (however, subscripts '1' in our plots in this lab), and the other higher modes with higher n are called <u>overtones</u>. Phase velocities V_n depend on frequency ω, and this dependence is called <u>phase velocity dispersion</u>. These dependencies $V_n(\omega)$ are measured from the seismic records. By modeling these dependencies in a layered structure, the subsurface model is derived.

If a surface-wave wave mode with phase velocity $V_n(\omega)$ is present in the data, then its wavelength is given by the same relation as above: $\lambda_n(\omega) = \frac{V_n(\omega)}{f} = 2\pi\frac{V_n(\omega)}{\omega}$. This mode samples depths roughly equal half of this wavelength:

$$z_n(\omega) = \frac{V_n(\omega)}{2f} = \pi\frac{V_n(\omega)}{\omega}, \quad (2)$$

Similar to electrical imaging, for example, this characteristic depth of sampling is called the psudo-depth of MASW imaging.

Relation (1) means that for any fixed ω, the amplitude of the nth mode is a periodic function of distance x: $u_n(x,\omega) = A_n e^{i\omega\frac{x}{V_n}} = A_n e^{i\omega s_n x}$, where $s_n = 1/V_n$ is the slowness. To identify this periodic function in the data, the following processing is applied:

1) The data records at locations x_i ($u(x_i, t)$) are Fourier transformed, giving complex-valued frequency-domain data $u(x_i, \omega)$;
2) For a range of trial slowness values s, a semblance function is calculated:

$$semblance(\omega, s) = \left| \sum_i \left[e^{-i\omega s x_i} \frac{u(x_i,\omega)}{|u(x_i,\omega)|} \right] \right|. \quad (3)$$

The purpose of this semblance measure is that if wave mode n with slowness s_n is present in the data, then the terms in the square brackets will depend on x_i as $e^{i\omega(s_n - s)x_i}$. With trial s equal s_n, all these terms will equal one, and the sum will attain the largest value. By picking the value of s at which $semblance(\omega,s)$ is the largest for a given ω, the slowness of the nth mode $s_n(\omega)$ can be determined. Other semblance functions showing peaks at $s = s_n$ can also be constructed.

In this lab, you will evaluate the $semblance(\omega,s)$ function (2) for several shots from the 2021 field school dataset, identify the fundamental Rayleigh-wave mode in it, and try inverting its $s_n(\omega)$ (with $n = 0$) for a layered structures beneath the shots. Most of the data analysis and processing has already been performed and Matlab code written, and so you will only need to focus on performing inversions and understanding the results.

Assignments

1) **Download and unpack archive file `lab3.zip`.** This file contains directory `lab3` in which you will find:

- Directory `data` containing several Matlab workspace (.mat) files. Each of these files contains a record from one shot (in Matlab structure `rec`), its spectra (in structure `spec`), and its semblance spectra (eq. (2)) in structure named `dispsemb`.
- Directory `matlab` containing several Matlab function used for processing and assessing the data.
- Directory `modeling` containing Matlab functions used for inversion of the phase-velocity (semblance).
- Script `lab3.m` with an outline of the work. You will need to modify the file.

2) **Try executing script** `lab3.m` in Matlab. I developed the codes in GNU Octave but tried staying compliant with Matlab. However, a small number of syntax errors such as occasional use of keywords like 'endif' is possible. Try correcting these errors and report them to me.

   The initial example in `lab3.m` is given for FFID number 153. The record including its spectra and semblancies loaded by function `record_ffid()` and plotted using `plot_ffid1()` and `plot_dispersion()`. **Attach these plots to the lab report**. I**dentify the surface waves and the fundamental mode** in the phase semblance plot. An example of the semblance plot is shown with additional comments in Fig. 1.

   The layered velocity-density model is listed in variable `model0` at the beginning of the script gives my initial approximation to the data from the current FFID 153. This model is used to create the structure `model` in function `set_model()`. Then, this structure is further used to generate the set of wave modes and again plot the semblance with an overlay of the modeled phase-slowness curves (function `modes_rayleigh()`).

   Function `modes_rayleigh()` creates a figure with three images shown in Fig. 1, Fig.2, and Fig. 3. Looking at these images, your task is to adjust the velocity model (Fig. 2) so that the modeled phase-slowness curves (Fig. 1) match the observed ones as closely as possible.

3) Try adjusting the velocity model to achieve a better fit of the phase slowness curve to the peaks of semblance for the fundamental mode. The adjustments may be easier to perform by scaling both the V_P and V_S velocities at once. **To make these adjustments, simply change the factors for each layer** in column `scale V.` Looking at the relations between the depth- and pseudo-depth plots (red lines in Fig. 2) suggests the amounts of these scalings needed.

   From eq. (2), higher-frequency waves are affected by shallower layers and the lower-frequency ones are generally affected by all layers down to the pseudo-depth. Therefore, it is better to start by fitting the high-frequency part of $s_n(f)$ by modifying the shallow layers, and then proceed to the lower frequencies and deeper. However, you will likely see that it is impossible to fit every detail in the semblance plot. This is because the surface waves are affected by multiple layers simultaneously.

4) **Repeat the same procedure for FFIDs 143, 163, and 172**. They are spaced approximately evenly along the profile.

5) **Discuss the resulting semblance spectra and velocity models**. Is there a significant velocity variation with depth present? Does it look like a gradual increase with depth or pronounced contrasts between layers? Is there a significant lateral variation along the profile?

Hand in:

Codes `lab3.m` (and others if errors detected), plots, and report by email.

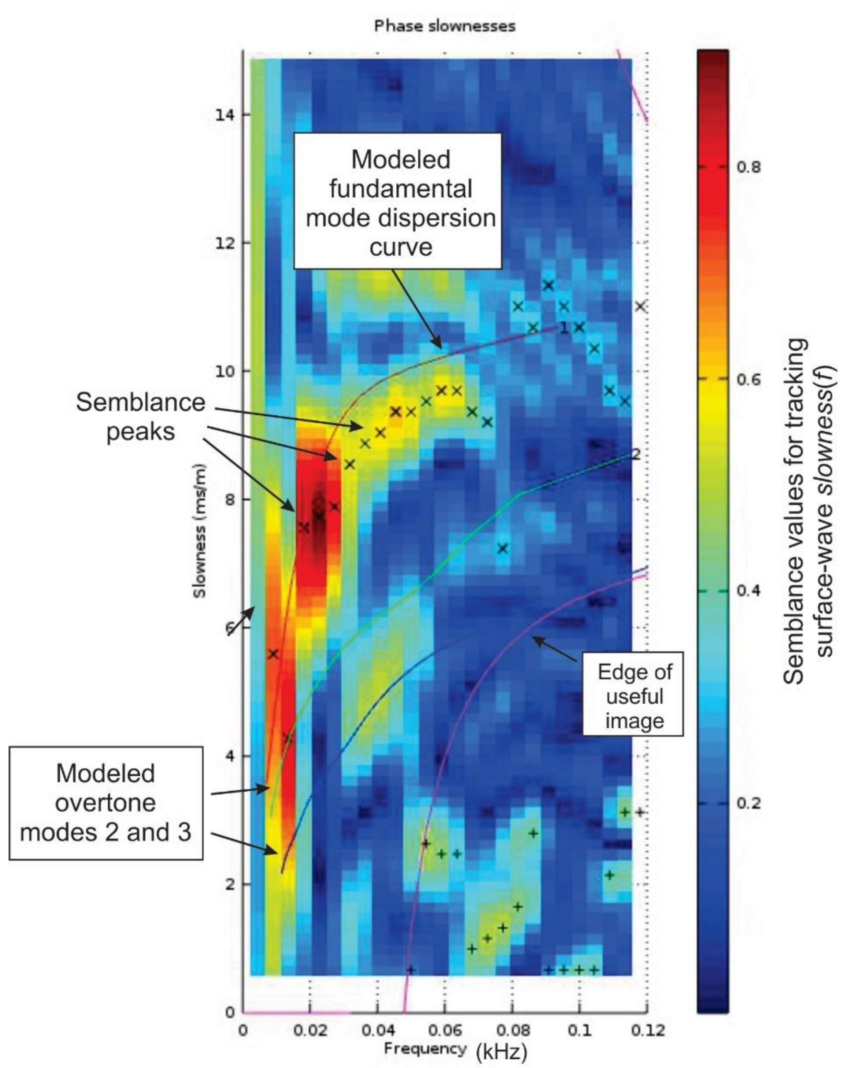

Figure 1. Phase semblance plot for FFID 153 with modeled slownesses $s_n(f)$. Crosses are the peaks of the semblance function; however, in your modeling, try fitting not strictly to these peaks but to the general trend of the red and yellow maxima of the semblance.

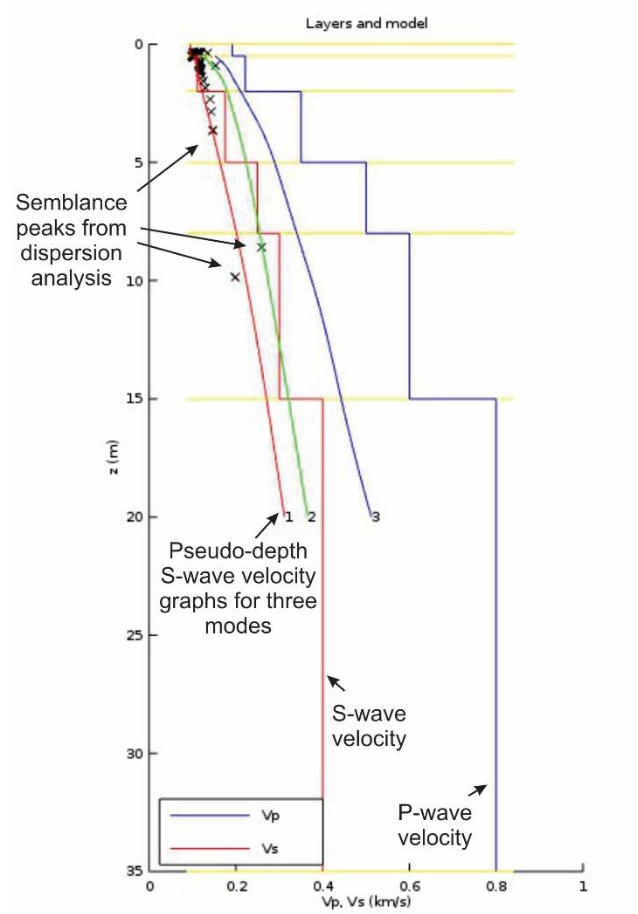

Figure 2. The layered P- and S-wave velocity depth model, pseudo-depth (eq. (2)) model for three modes (the one labeled ‘1’ is the fundamental mode $n = 0$). The velocities in the pseudo-depth model equal the surface-wave phase velocities divided by 0.9. This division gives an approximate estimate of the S-wave velocity. Thus, <u>you can generally expect that the red pseudo-depth curve will be close to the actual S-wave velocity curve</u>.

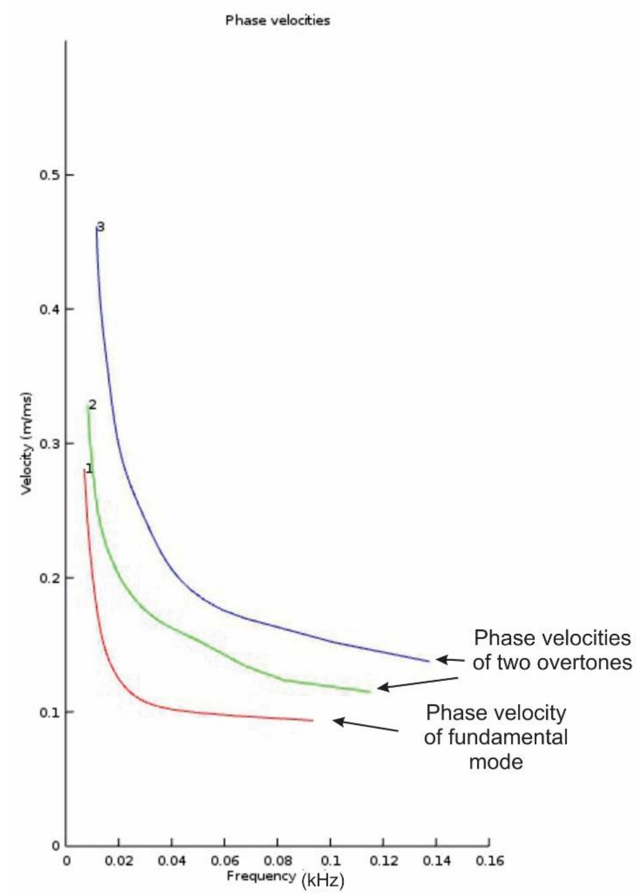

Figure 3. Modeled phase velocities vs. frequency for three lowest wave modes.