

Lamb Wave Patterns

Inversely dispersive velocity trends, i.e., phase velocity increasing with frequency.

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INTRODUCTION

Typically, Lamb-wave patterns can be observed when there is a high-velocity stiff layer at the top of a near-surface section. In such instances, some parts of the dispersion curves may exhibit features that resemble Lamb-wave (plate wave) patterns and not Rayleigh wave, "... free Rayleigh waves can only propagate at phase velocities slower than the shear-wave velocity of half space" (Thrower, 1965).

When applying the MASW method on structures with reverse velocity trends (i.e., velocities decreasing with depth), then for wavelengths up to five times that of the top stiff layer (Martinček, 1994) the dispersion-curve images may exhibit Lamb-wave patterns. In such cases, the overall trend consists of a sequence of multi-mode events observable within narrow frequency ranges (i.e., small portions of higher modes), almost node-like, which when viewed together can shape a different trend (Figure 1a). Mode identification becomes difficult with such images and even if accurate, using the conventional Rayleigh-wave inversion algorithms (which assume that a half space has the highest velocity) may not be numerically appropriate. Furthermore, using a shorter spread for higher lateral resolution (i.e., lesser averaging within the spread) may blur all these numerous-mode energies into a single reverse "apparent" trend (Figure 1b) and thus "hide" individual mode contributions.

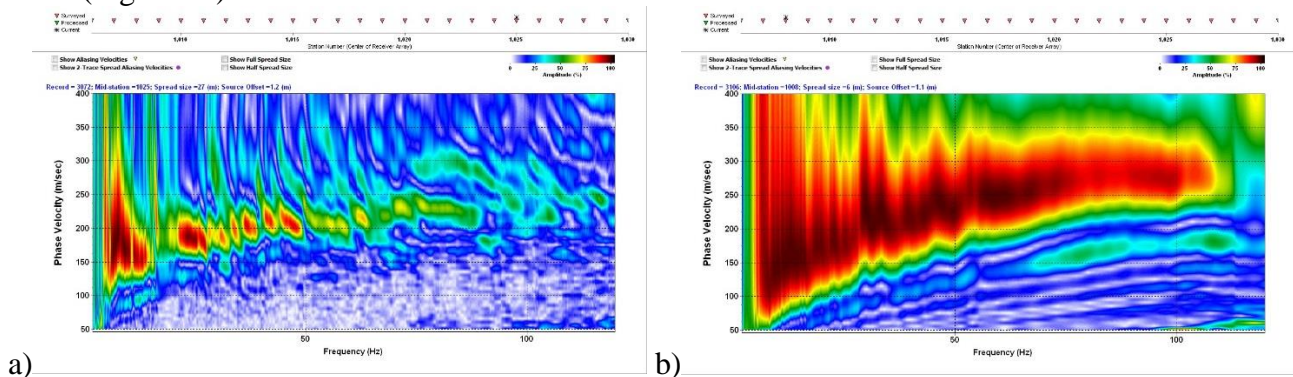


Figure 1. Dispersion-curve images of record 1012 using a a) large, 24 m spread, and a b) short, 6 m spread from using the phase-shift method.

NUMERICAL MODELS

Research by Pan et al. (2013b) continue previous efforts (Phinney, 1961; Schroder and Scott, 2001; Ryden et al., 2004) in using the real part of the complex roots of the Rayleigh-wave equation (a.k.a. leaky-waves) as phase-velocities of Rayleigh waves (Cf) and showed that a subset of multi-mode dispersion-curve points (events) is numerically equivalent to that of a fundamental-mode dispersion curve from a substitute model that uses only the top 2 layers of the original model (consisting of 3 or more layers).

Beginning with SurfSeis v.4, users are able to obtain such a simple 2-layer reverse velocity trend solution, i.e., a high-velocity layer on top of a lower-velocity half space. However, the conventional Rayleigh-wave initial model creation (default in SurfSeis) will most likely be unsuitable and some inversion tune-up may be necessary. Following is an example of the inversion steps needed when dealing with Lamb-wave data patterns.

We used a three-layer model similar to the one studied by Ryden et al. (2004) (but at a greater scale) (Table 1) to calculate synthetic seismic data using KGS's software (SynthSeis, soon to be released)

H	Vs	Vp	Density
5	1000	2000	2.0
10	419	1050	1.9
HS	96	318	1.8

Table 1. Three-layer model used to calculate synthetic seismic data, where H is layer thickness, Vs is shear velocity, and Vp is compressional velocity. [is “density” self-explanatory?]

Next, a dispersion-curve image was obtained and the first 6 modes were calculated (Figure 2). Following the overall reverse velocity trend with the intent of treating it as resulting from a 2-layer model, a reverse-trend (i.e., velocities increasing with frequencies) dispersion curve was picked (Figure 3).

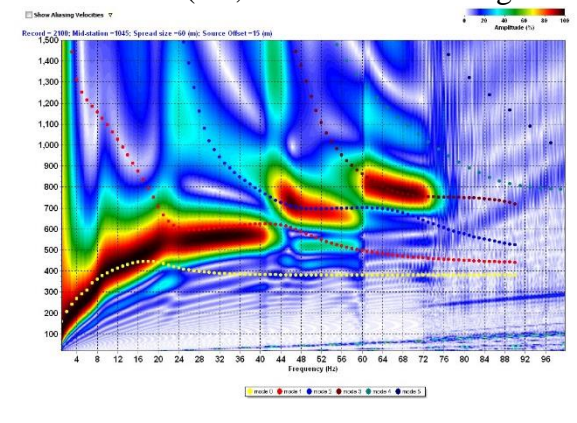


Figure 2. Dispersion-curve image obtained and 6 calculated dispersion-curve modes.

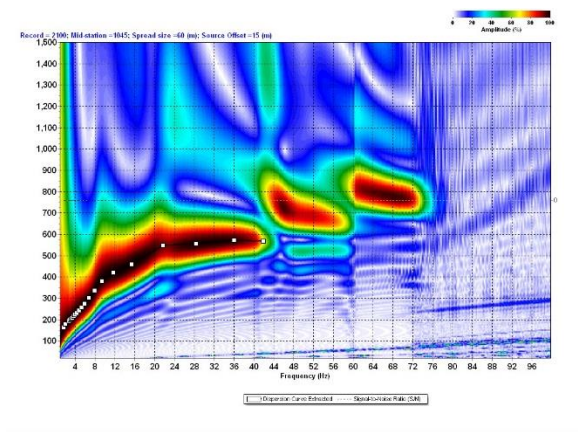


Figure 3. Dispersion-curve estimation.

The conventional Rayleigh-wave initial model generation algorithm using half-wavelength depth and $Cf = 0.92 V_s$ assumptions did not provide adequate inversion results. Another approach was needed for coming up with an initial 2-layer model.

The main trend asymptotic velocity at 40 Hz is about 600 m/s and corresponds to ~15 m wavelength. Knowing that the synthetic model thickness and V_s are 5 m and 1000 ms accordingly, the initial model algorithm for this case can be adjusted so depth = ~33% wavelength depth and $V_s = \sim Cf/0.6$.

However, following Ryden et al. (2004), another reference point can be used, such as ~720 m/s at 72 Hz when considering the trend formed from all modes. The corresponding estimates would be 10 m wavelength, top layer thickness = ~50% wavelength, and $V_s = \sim Cf/0.72$.

One way to run the inversion in SurfSeis 4 or newer with this type of initial model tune-up can be accomplished by the following steps:

1. Copy an existing layer-model file (.lyr) and edit it into a 2-layer model with the top layer thickness and V_s parameters estimated with an algorithm similar to the one above.
2. Open a .dc file from “Invert Dispersion curves”.
3. Click the “Controls” button, “Initial Layer Model” tab, and at the “Initial S-Velocity” radio group select “Fixed data in layer table”.
4. Click the “Layer” button, Import Model (*.LYR)” button and read the specially created 2-layer model file created in step 1.
5. Adjust iteration parameter to your judgment, if necessary (“Controls” button, “Iterations” tab).

Using the estimated dispersion curve (Figure 3) and following the above approach, a simple 2-layer Lamb-wave inversion solution was obtained.

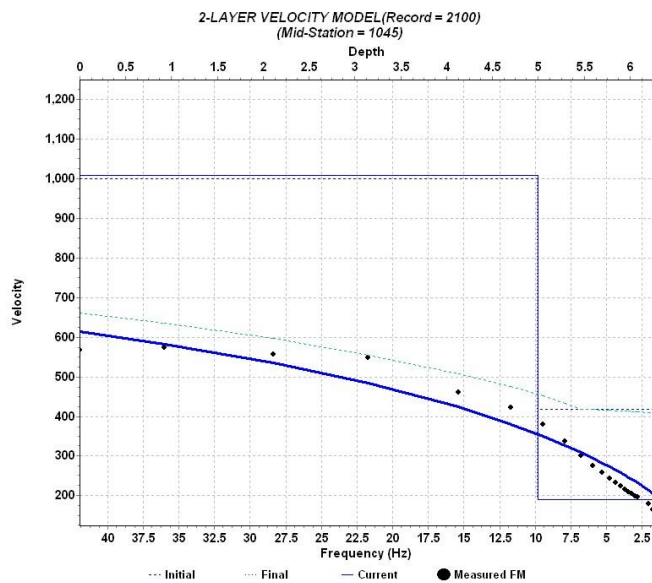


Figure 4. 2-layer model inversion results and corresponding dispersion curve fit to the observed data points.

The calculated dispersion curve fit is not perfect, but still provides an overall match to the data from a 3-layer model. A better match can be obtained if using fewer lower-frequency points, e.g., above 10 Hz, etc. (Pan et al., 2013a). The velocity of the top layer was estimated within ~1% error ~1010 m/s and the velocity of the half-space (~190 m/s) was estimated between the values of the second layer and the half-space of the synthetic model (Table 1).

The initial model generation parameters (H, Cf, etc.) may be different for other cases (velocity models, source offset and spread size, observed frequency range, etc.) and should be regarded only as an example of the complexity when dealing with Lamb-wave patterns.

Pan et al. (2013a) suggest a more complicated algorithm for dealing with high-velocity surface layer models that have 3 or more layers. If proven robust, such an algorithm might be implemented in future versions of SurfSeis (i.e., 7 and higher).

REAL-WORLD DATA APPROACHES

With the difficulty of identifying modes and obtaining accurate numerical solutions, it is possible to pick the overall energy trend without identifying modes, i.e., treat it as fundamental mode (Figure 5) for qualitative evaluations. There are two major possibilities to use these picks:

Initial-model

The simplest qualitative approach is to open the .dc files for inversion and use half-wavelength (or smaller; e.g., 30%) approximation, which can be used as a “qualitative” tool to observe lateral Vs variations. With SurfSeis this can be achieved by viewing the initial Vs model at the “Initial Vs” tab, if it is derived from each dispersion curve (Figure 6). For tasks that require lateral anomalous-zone detections, such an approach could be sufficient.

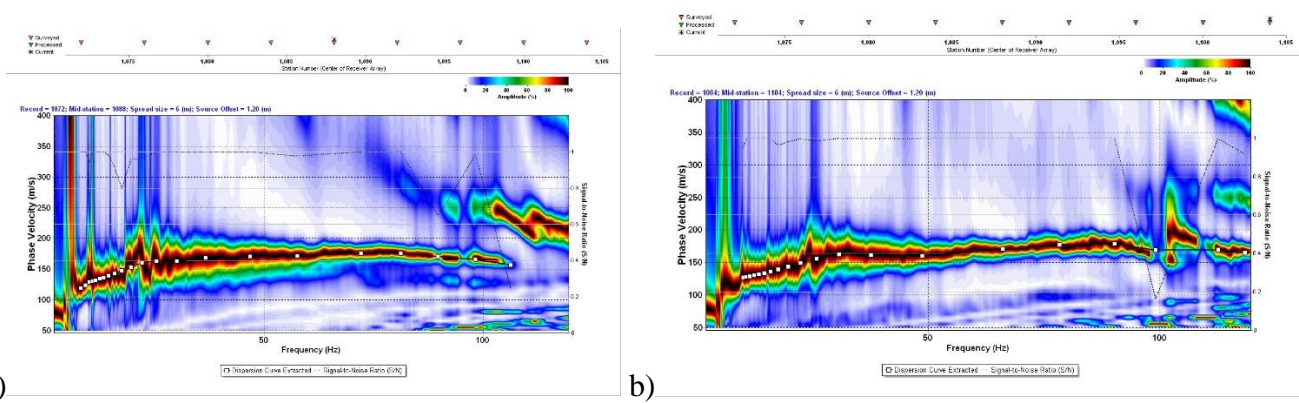


Figure 5. Dispersion-curve images of records a) 1072 and b) 1084 from using very short (6 m) spreads with the HRLRT.

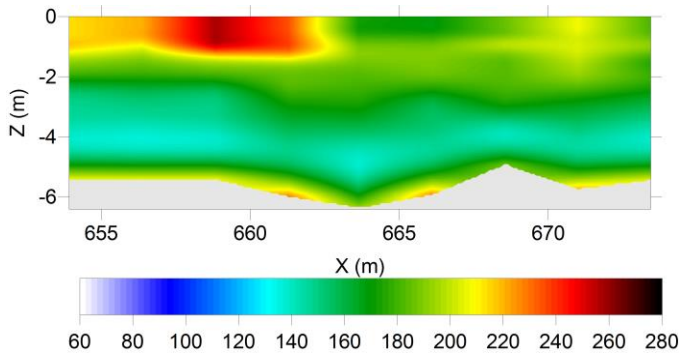


Figure 6. 2D Vs initial model from nine dispersion curves.

Inversion

In real-world settings, the velocity contrasts between layers (and overall gradient) may be small, i.e., the inverse velocity trend may be insignificant. In such cases, observing an inversely dispersive fundamental trend can be a possibility in the real world. Such curves can be inverted in the conventional manner (Figure 7) and a 2D Vs model can be obtained (Figure 8). Furthermore, the smaller the relative velocity pull down at lower frequencies and emphasis of Lamb-wave patterns, the greater the chance for numerical accuracy.

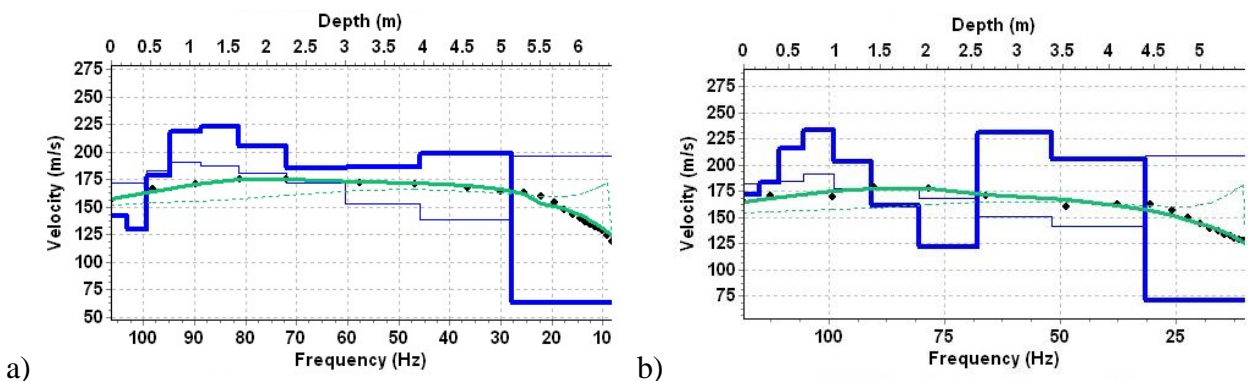


Figure 7. Inverse-dispersion Vs inversion results (thick blue lines) from records 1072 and 1084. Black points and the green line indicate the picked and calculated apparent modes, respectively.

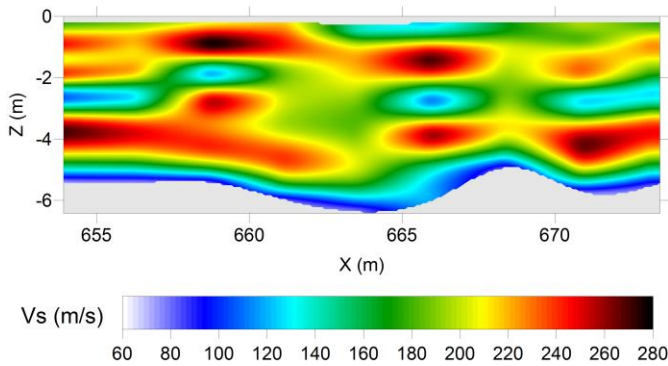


Figure 8. 2D Vs results from inverting nine dispersion curves.

To evaluate the inversion results, users can perform modeling on dispersion curve images (“Tools”, “Modeling And Random Inversion” from the main menu) using a dispersion curve image of a selected record and the corresponding .LST file from the inversion to populate the model parameters (Figure 9).

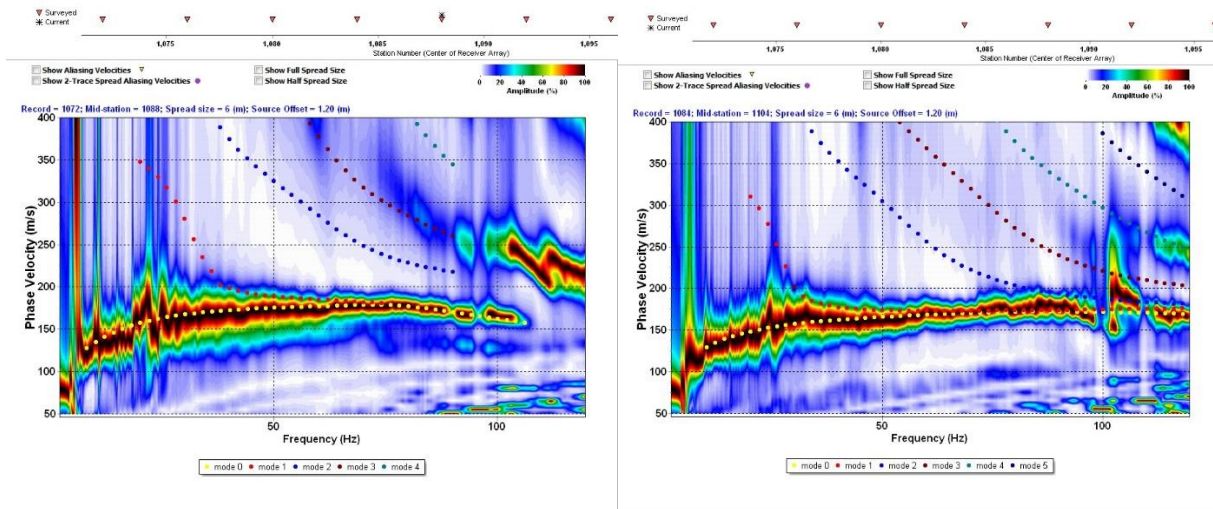


Figure 9. Modeling on dispersion curve images of records 1072 and 1084

REFERENCES

- Martinček, G. v., 1994, Dynamics of pavement structures: Spon.
- Pan, Y. D., J. H. Xia, L. L. Gao, C. Shen, and C. Zeng, 2013a, Calculation of Rayleigh-wave phase velocities due to models with a high-velocity surface layer: *Journal of Applied Geophysics*, **96**, 1-6.
- Pan, Y. D., J. H. Xia, and C. Zeng, 2013b, Verification of correctness of using real part of complex root as Rayleigh-wave phase velocity with synthetic data: *Journal of Applied Geophysics*, **88**, 94-100.
- Phinney, R. A., 1961, Leaking Modes in Crustal Waveguide .1. Oceanic PI Wave: *Journal of Geophysical Research*, **66**, 1445-1469.
- Ryden, N., C. B. Park, P. Ulriksen, and R. D. Miller, 2004, Multimodal approach to seismic pavement testing: *Journal of Geotechnical and Geoenvironmental Engineering*, **130**, 636-645.
- Schroder, C. T., and W. R. Scott, 2001, On the complex conjugate roots of the Rayleigh equation: The leaky surface wave: *Journal of the Acoustical Society of America*, **110**, 2867-2877.
- Thrower, E. N., 1965, Computation of Dispersion of Elastic Waves in Layered Media: *Journal of Sound and Vibration*, **2**, 210-226.