Active and Passive Surface Wave Testing: Addressing Uncertainty using Open-Source Tools

Reviewing and Evaluating Reports and Papers on Surface Wave Testing

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What Should be In a Report?

- Demand (or provide) reports with the following information:
  1. Acquisition:
     a) Array geometry, equipment used, source type, source locations, etc. (text, maps, pictures)
  2. Processing:
     a) Methods and software used
     b) Plots of dispersion images/data
     c) Some explanation about how dispersion data was selected relative to various array resolution criteria
     d) Description of how uncertainty in dispersion data was quantified or why it was ignored
     e) Tables of final dispersion data used for inversion Optional, but can be very helpful
  3. Inversion:
     a) Methods and software used
     b) Plots of experimental dispersion data and theoretical fits on the same figure.
     c) Plots and tables of V_S profiles with clear indication of maximum depth resolution relative to wavelengths extracted during processing and/or array dimensions
     d) Description of how uncertainty in Vs profiles was quantified or why it was ignored

     Non-negotiable! This is the item I see missing the most.
  4. Some "good", site specific discussion about uncertainty in the results… not some disclaimer that all geophysical methods may or may not be correct.

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Examples of What We Actually See in Reports and Papers…

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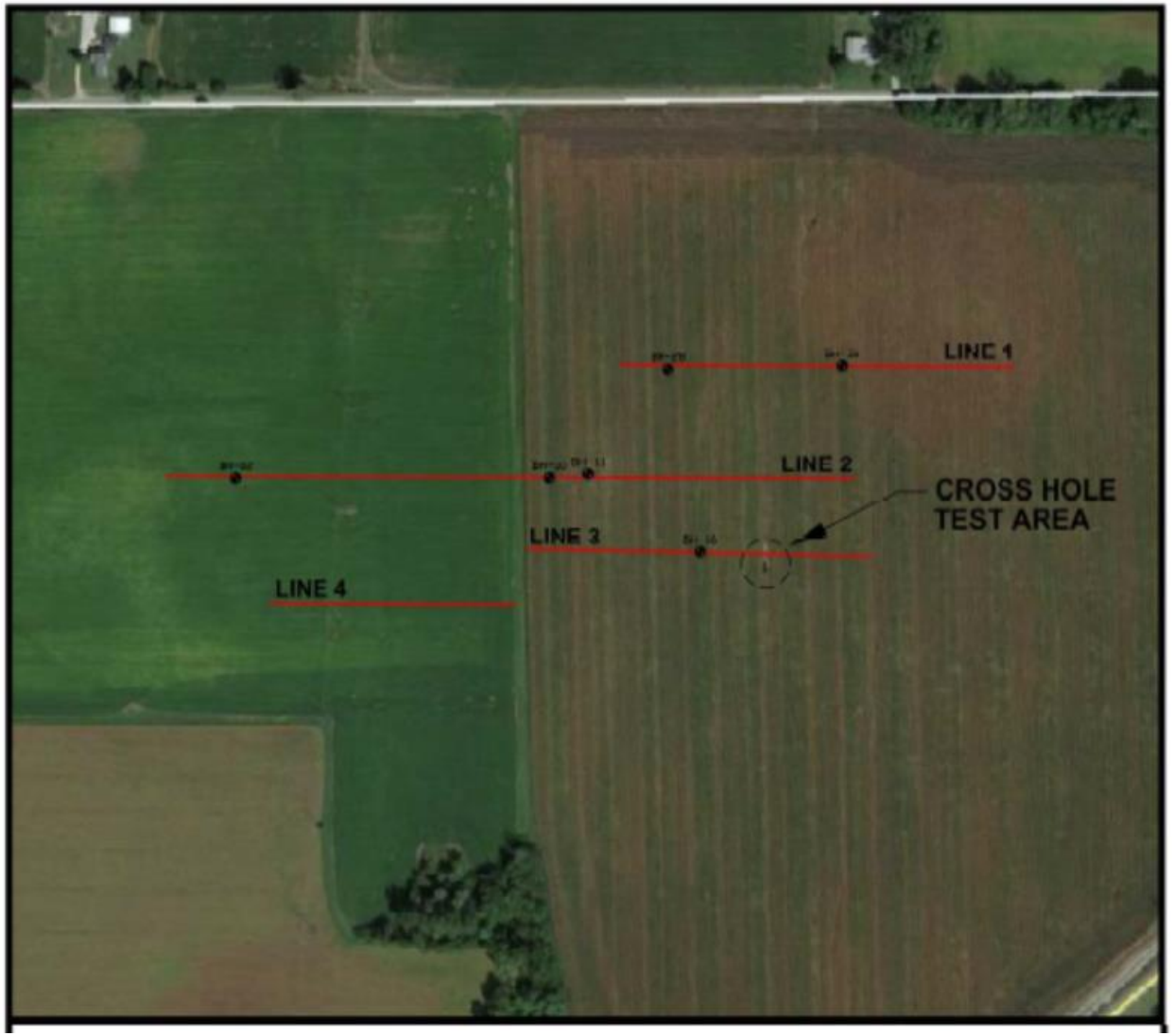
Example #1: 2D MASW Report

- A 2 billion dollar facility
- 3,500 ft of “2D” MASW
- Vs profiles every 20 ft
- 175 tabulated Vs profiles
- 1.5 page report
- No dispersion data
- No Vs plots
- Vs30 = 600 – 1200 fps
- 3 of these tabulated Vs profiles were randomly selected for use in seismic site response analyses

Cox to show redacted pdf report



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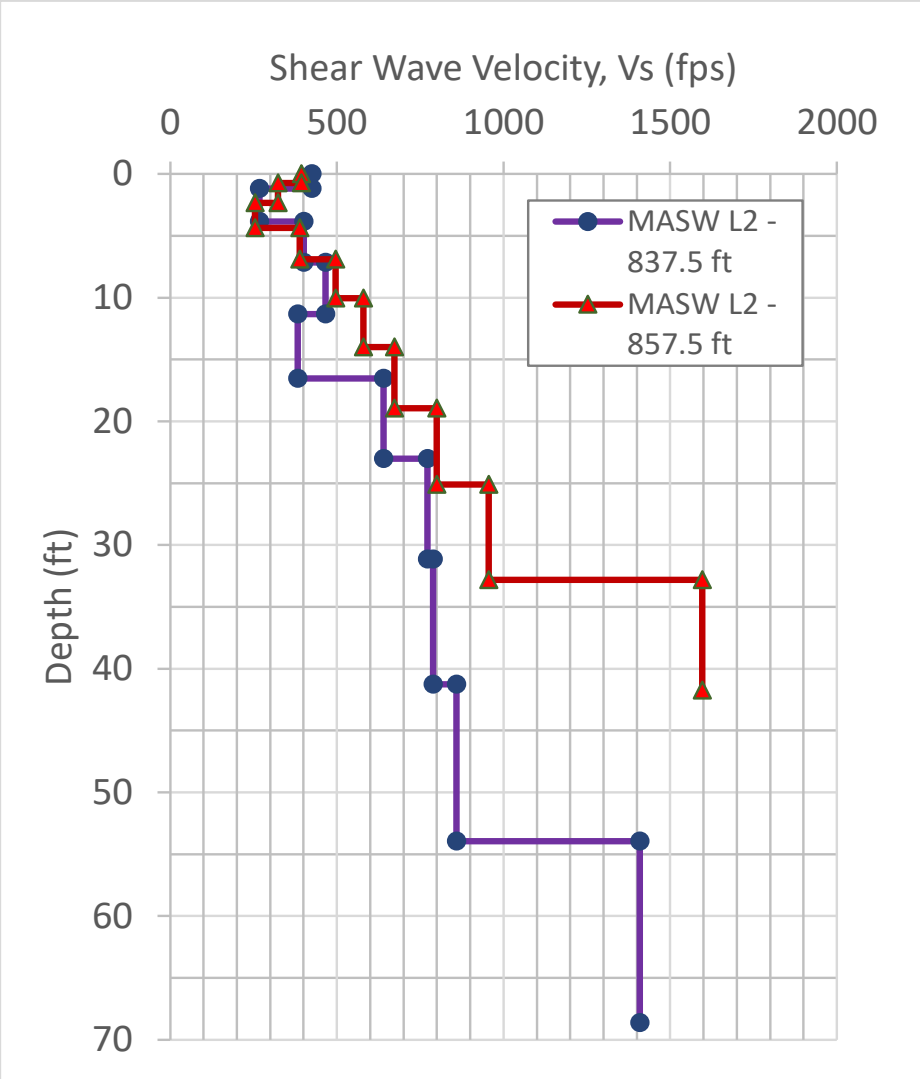
Example #1: 2D MASW Report



I was curious, so I plotted two of the Vs profiles that were adjacent to each other (20 ft apart).

- No comparison to XH results
- No comparison with 85 borings and 22 CPT at site
- X-sections from boring logs indicate minimal variation in depth to bedrock over short distances
- Geophysical disclaimer in the report…

> The MASW method is a non-intrusive, indirect geophysical method based on transmitting and recording seismic waves that are potentially affected by a variety of natural or man-made conditions. The potential for detecting the presence or absence of subsurface features is based on the quality of the recorded data as limited by site conditions, and on the interpretation of the data received. Hence, there will always be the potential of not observing a subsurface object or interpreting the presence of a subsurface object where one does not exist. We strongly suggest that the results of the geophysical surveys be verified with an invasive exploration method such as drilling.

In my opinion, this work and reporting is unethical, whether out of:

a) Ignorance (operating out of areas of competence), or

b) Dishonesty and laziness to make a profit

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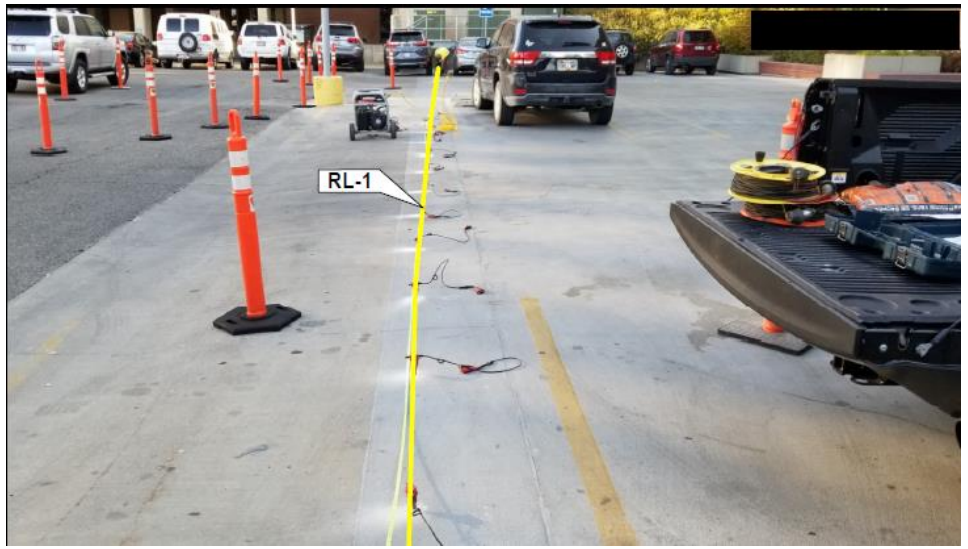
Example #2: 2D ReMi Report

- For seismic site classification and potentially locating a fault
- Two – 2D ReMi lines and one – 1D ReMi array
- 24, 4.5Hz geophones spaced at 4 ft (92-ft long arrays)
- Roll-along moveouts of 4ft to 8ft
- Only noise acquisition
- No discussion about data acquisition times
- No dispersion images or data picks shown
- No theoretical fits to dispersion data provided
- Vs profiles generated down to 100 ft (= to array length), even though they probably should have only been reported to 50 ft.



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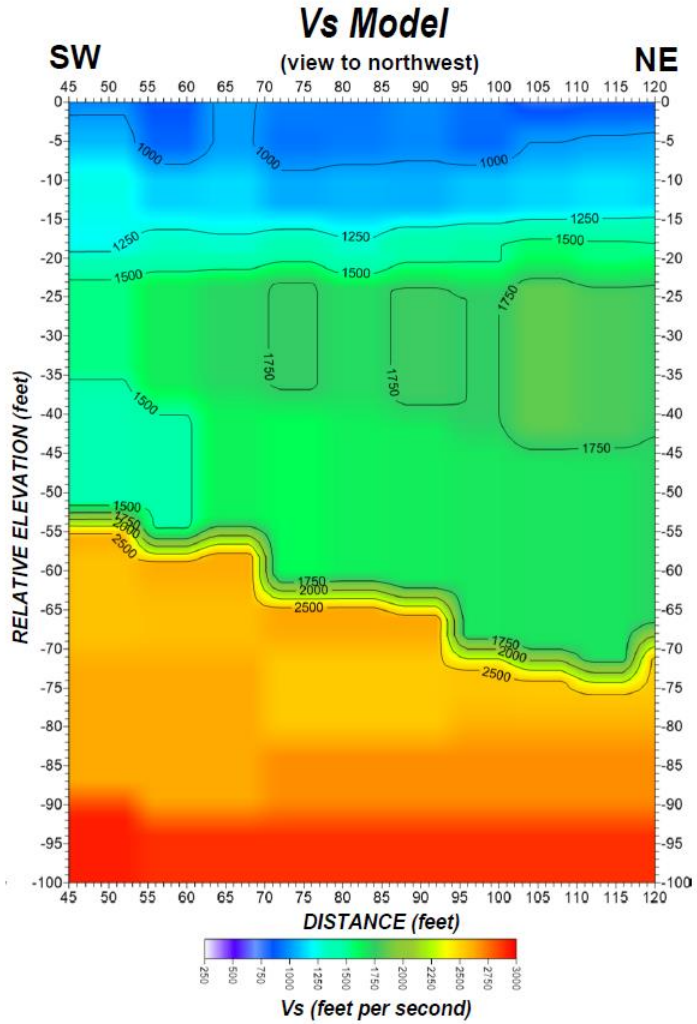
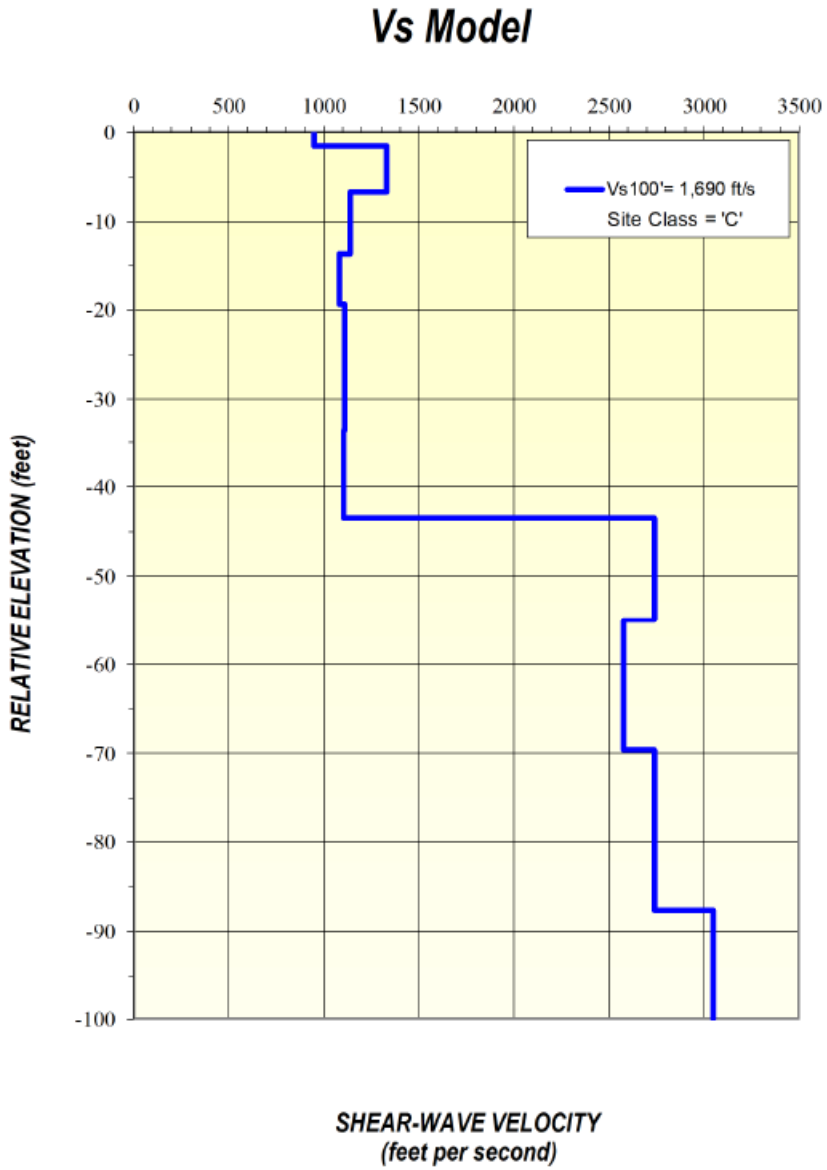
Example #2: 2D ReMi Report





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Example #2: 2D ReMi Report

7. LIMITATIONS

The field evaluation and geophysical analyses presented in this report have been conducted in general accordance with current practice and the standard of care exercised by consultants performing similar tasks in the project area. No warranty, express or implied, is made regarding the conclusions and opinions presented in this report. There is no evaluation detailed enough to reveal every subsurface condition. Variations may exist and conditions not observed or described in this report may be present. Uncertainties relative to subsurface conditions can be reduced through additional subsurface exploration. Additional subsurface evaluating will be performed upon request.

Well that's scary! I happen to know that what was done in this report violates John Louie's recommendations for ReMi Vs30 measurements.

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Example #3: Vs100 Seismic Site Classification Report

The report started off strong! This table of acquisition parameters is great!

Table 2 Seismic Survey recording parameters – V_{S100}

Test location	[redacted]
Recording instrument	DMT Summit Extreme Pro
S/N	SUX1018
geophone natural period	4.5 Hz.
geophone/station spacing	6.56 ft. (2 meters)
number of channels	24
spread length	150 ft.
sample rate	4 millisecond
number of samples	15,000 per channel
record length	60 seconds
low pass filter	½ Nyquist
low cut filter	1 Hz.
seismic source	16 lb. sledgehammer
source location	-30 feet offset
Analysis software	Surfseis™ surface wave inversion, Geometrics, Inc.

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Example #3: Vs100 Seismic Site Classification Report

But, it went downhill fast! This is the entire description of data acquisition and processing.

Seismic Velocity Survey V_{S100}

Seismic Surface Waves methods such as MASW (Multichannel Analysis of Surface Waves), MAM (Microtremor Array Measurements), and ReMi (Refraction Microtremor) use the dispersive characteristics of surface waves to determine the variation of the seismic shear wave velocity with depth. Velocity data are derived by analyzing seismic surface waves generated by a controlled impulse or by random sources and received by an array of geophones.

A dispersion curve is calculated from the data that shows the phase velocity of the surface wave as a function of frequency or wavelength. A shear wave velocity profile (a 1-D sounding of velocity as a function of depth) is then modeled from the dispersion curve and the shear velocity of the near surface is calculated.

The the ambient MAM data was suplimented with 10 minutes of hammer blows to produce a smooth broad spectrum curve. The results are presented Appendix B.

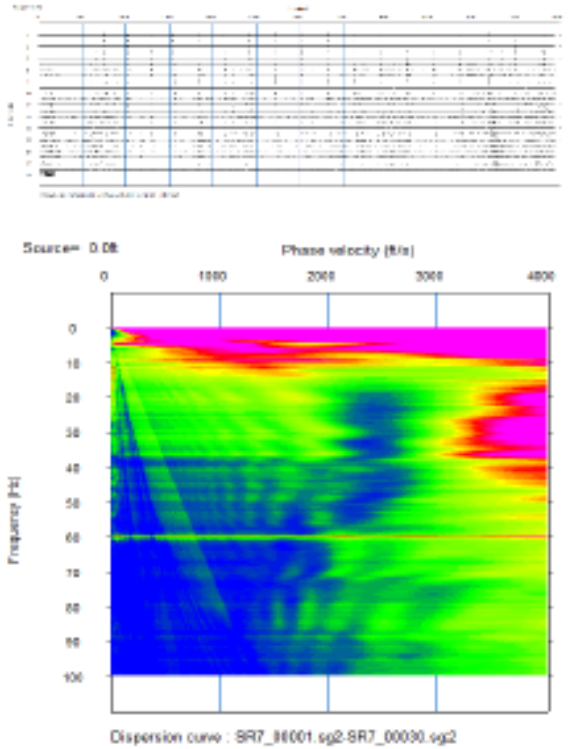

Figure 2 Phase vs. velocity plot (microtremor array measurement-MAM)

One short sentence related to site-specific collection information.

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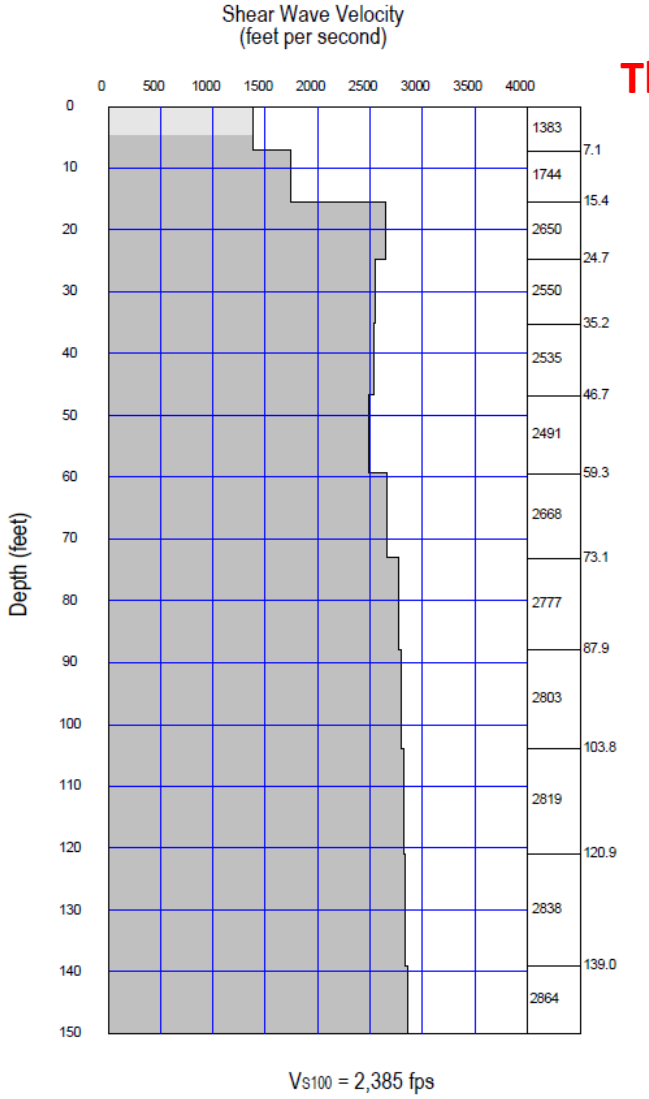
Example #3: Vs100 Seismic Site Classification Report

- No dispersion picks on the single, microscopic image
- No theoretical fits to dispersion data provided
- Vs profile generated down to 150 ft (= to array length), even though they probably should have only been reported to ~ 75 ft.

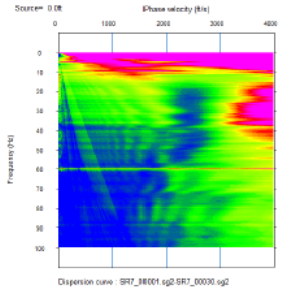
In my opinion, this work and reporting is unethical, whether out of:

a) Ignorance (operating out of areas of competence), or

b) Dishonesty and laziness to make a profit



This is Appendix B in its entirety.



phase vs velocity plot
(dispersion curve)

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Example #4: 2D MASW for Anomaly Detection and 1D ReMi for Vs100

This report provides some really nice information:

Our scope of services for the project included:

- Performance of two 2-D MASW shear wave seismic lines at the project site (Figure 2).
- Performance of two 2-D ERT lines at the project site (Figure 2).
- As a value-added service, we added performance of a single one-dimensional (1-D) refraction microtremor (ReMi) sounding at a portion of ML-2 at the project site during our field tasks (Figure 2) which is useful for evaluation of site specific Vs30 and/or seismic Site Class.

I don't like this statement, but the rest is very good.

The surface wave (s-wave, analogous to shear wave) MASW seismic evaluation was conducted using a Geometrics StrataView, 24-channel seismograph and twenty-four 4.5 hertz (Hz) geophones on a Geostuff landstreamer data collection unit. The seismic source was a manually operated 16-pound steel sledgehammer and an HDPE plastic strike plate. The geophones were spaced 5-feet apart and the surface wave data was collected in a roll-along method whereby the geophone array was shifted approximately 10-feet after each data collection event. Seismic and ERT traverse locations were recorded in the field using

L = 115 ft

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Example #4: 2D MASW for Anomaly Detection and 1D ReMi for Vs100

A relatively short geophone spacing was designed to enhance near surface resolution of anomalies in the subsurface. Prior to the collection of surface wave data at each seismic transect location, near and far field effects were evaluated for several seismic source shot off-end distances. MASW shot points (signal generation locations) were conducted at an off-end distance during roll-along data collection that was selected based on results from our onsite test shots from the record producing a high amplitude and coherent fundamental in the phase velocity versus frequency curve. The results of our off-end shot testing indicated that an off-end shot distance of 20 feet was optimal for both ML-1 and ML-2.

This is a very nice description of how they tried to mitigate near- and far-field effects!

Source offset = 20 ft

Depth of evaluation in the MASW method is dependent upon the frequency content of recorded signals and depends on site conditions. Three records, each 1 second long, were recorded at each shot location and then the shot location and the landstreamer were moved longitudinally along the profile direction and the line was shot again.

I can completely understand how they collected the data.

Our ReMi evaluation included the use of a 24-channel Geometrics Geode seismograph and 24, 4.5-Hz vertical component geophones. The geophones were spaced 5 feet apart for a total line length of 115 feet near the eastern end of MASW line ML-2. A total of 15 records, each 32 seconds in duration, were recorded utilizing passive data collection of ambient ground vibration. The recorded data was then downloaded to a field computer.

L = 115 ft

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Example #4: 2D MASW for Anomaly Detection and 1D ReMi for Vs100

DATA PROCESSING

2-D MASW Seismic

The recorded MASW data were processed using SurfSeis® (Kansas Geological Survey, 2020), a MASW processing program. One dimensional (1-D) shear wave (S-wave) velocity profiles were generated using a stack of the three shots per shot location in software. Each 1-D model profile corresponds to the middle of the geophone array (midpoint solution) at each roll-along position. A 2-D color gradient seismic surface wave velocity model was then created from the 1-D models for each transect using the SurfSeis®

1-D Refraction Microtremor (ReMi)

As previously indicated, one refraction microtremor sounding was conducted as part of our study, near the southeast end of ML-2. The data were processed and analyzed using Surface Plus 9.1 - Advanced Surface Wave Processing Software (Geogiga Technology Corp., 2020), which uses the refraction microtremor method (Louie, 2001), and other surface wave analysis methods. The program generates phase-velocity dispersion curves for each record and provides an interactive dispersion modeling tool where the users determine the best fitting model. The result is a 1-D seismic surface-wave velocity model of the site at the location we evaluated which, based on published studies, is typically 85 to 95 percent of the velocity of shear waves. Therefore, using the ReMi surface wave data and analysis method results in a relatively conservative estimate of shear wave velocity.

Very minimal information about processing and inversion.

This is a very puzzling statement to me.

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Example #4: 2D MASW for Anomaly Detection and 1D ReMi for Vs100

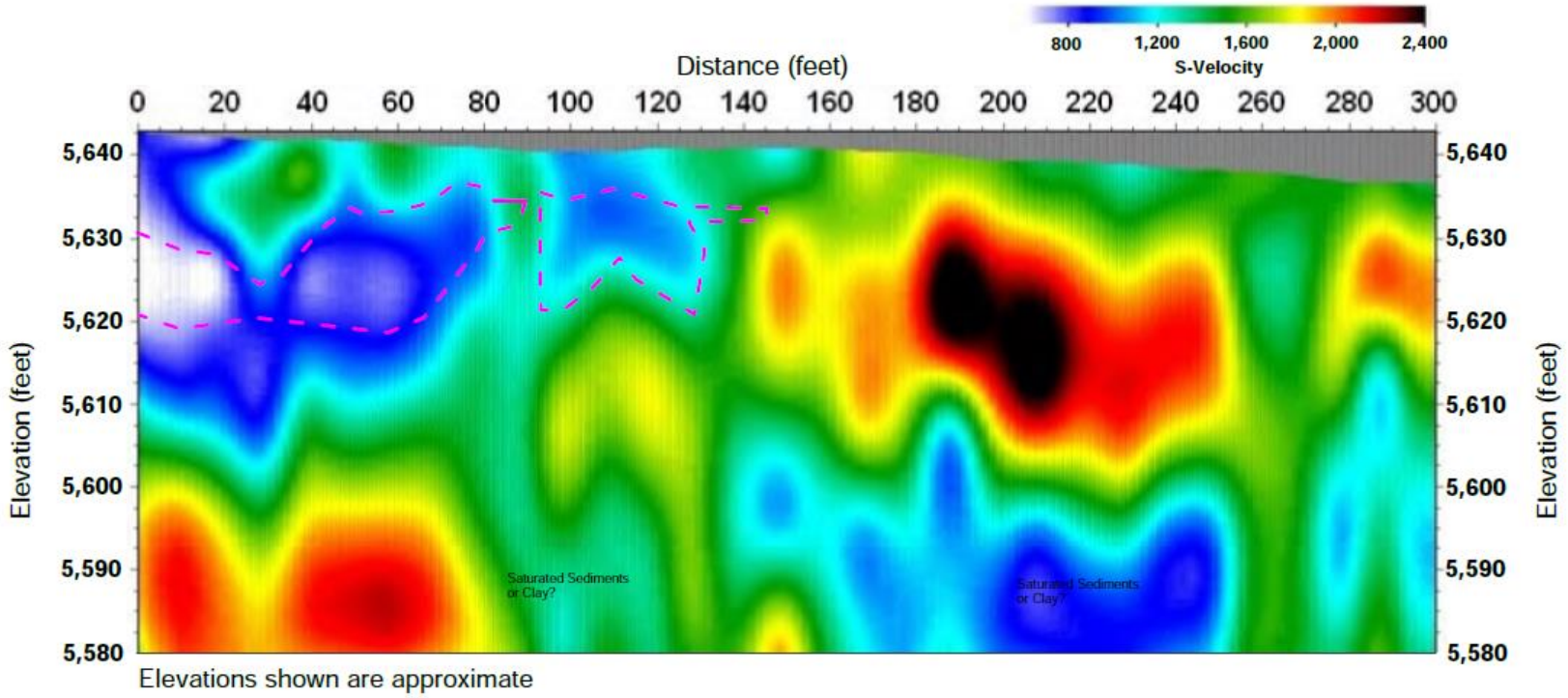
- No dispersion images or picks shown
- No theoretical fits to dispersion data provided
- Vs profiles generated down to 60 ft (~ 1/2 array length)… o.k.

Example of 2D MASW Results

I am skeptical. I would like to:

a) **See the dispersion data to observe if LVL are present in the dispersion**

b) **Know more about how the inversion was parameterized (e.g., number of layers and thicknesses, if velocity reversals were allowed in all layers, etc.)**



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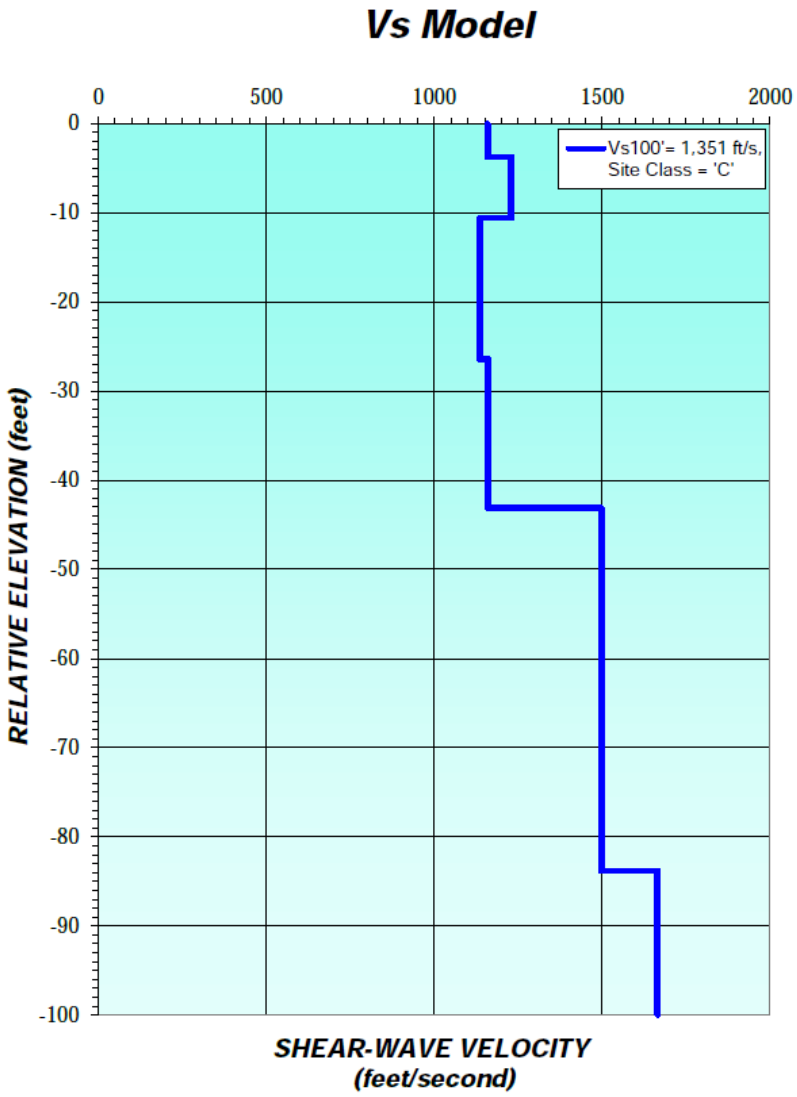
Example #4: 2D MASW for Anomaly Detection and 1D ReMi for Vs100

ReMi Results

- No dispersion images or picks shown
- No theoretical fits to dispersion data provided
- Vs profile generated down to 100 ft (just less than array length), even though they probably should have only been reported to ~ 60 ft.

Table 1 – ReMi Results

Line No.	Depth Range (feet)	Shear Wave Velocity (feet/second)
RL-1 (NW-SE)	0 - 4	1,159
	4 - 11	1,229
	11 - 26	1,136
	26 - 43	1,160
	43 - 84	1,498
	84 - 100	1,664



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Example #4: 2D MASW for Anomaly Detection and 1D ReMi for Vs100

Final thoughts on this example…

- I like the general philosophy of using 2D MASW and/or ERT to simply look for anomalies (voids, soft or stiff inclusions, highly variable bedrock), while using 1D methods to develop more reliable Vs profiles that can be used for Vs30 seismic site classification or seismic site response analyses.
- This report was stellar at documenting acquisition details, but lacked a lot of information related to processing and inversion. However, this VERY common.

Now You Know, You Can't Go Back!

- Surface wave testing is a powerful but "dangerous" tool.
- Be an educated provider… don't just push buttons.
- Be diligent about what you provide to clients.
- Be an educated end-user… don't just trust what someone gives you.
- Be extremely skeptical until contractors have proven that they do quality work.
- We have seen a lot of industry work that we consider to be unethical, whether out of:
  a) Ignorance (operating out of areas of competence), or
  b) Dishonesty and laziness to make a profit

Code of Ethics for Engineers

NSPE NATIONAL SOCIETY OF PROFESSIONAL ENGINEERS

Champion | Guide | Advance | Unite

https://www.nspe.org/resources/ethics/code-ethics

I. Fundamental Canons

Engineers, in the fulfillment of their professional duties, shall:

1. **Hold paramount the safety, health, and welfare of the public**.
2. **Perform services only in areas of their competence**.
3. Issue public statements only in an objective and truthful manner.
4. **Act for each employer or client as faithful agents or trustees**.
5. **Avoid deceptive acts**.
6. Conduct themselves honorably, responsibly, ethically, and lawfully so as to **enhance the honor, reputation, and usefulness of the profession**.

After this course, we would love it if more people would…

- Acknowledge uncertainties in surface wave testing (both dispersion and inversion).
- Start using the most robust methods whenever possible, and stop using inferior methods as a default just because its easier.
- Stop violating simple strategies related to near-surface layer thickness and maximum depth of Vs profiling relative to array geometry and accepted wavelength criteria.
  - Do not attempt to profile deeper than 1/2 to 1/3 of the maximum resolved wavelength.
  - Do not use near-surface layers thinner than 1/2 to 1/3 of the minimum resolved wavelength
- Stop putting LVL's in every inversion when they don't exist in the dispersion data.
- Improve reporting significantly (especially on processing and inversion).
- Provide more than 1 possible interpretation of the subsurface.
- Focus more on providing high-quality 1D Vs profiles than on providing an exorbitant amount of bad "2D" Vs profiles. There are needs for 2D/3D Vs profiling, but I believe it has to be done right, and should only be done when actually needed (not as a strategy to charge more money)

Discussion

- What can we all do to improve the state-of-practice while still providing timely and useful information?
- How much of the generally poor state-of-practice is caused by:
  1. A lack of knowledge/training
  2. Software companies marketing “easy-to-use”, push-button products
  3. The cutthroat business nature of under-bidding your competitors (do it cheap and fast because we aren’t getting paid much)
  4. Other factors?

Thanks for attending. We hope you learned something useful!

Final Comments or Questions?

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