Evaluation of Velocity (Vs) and Thickness (H)

Choon Park, Ph.D.

Principal Geophysicist
Park Seismic LLC

Seismic Approach to Quality Management of HMA

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Principal Investigator: ***Choon Park***, *Park Seismic LLC, Shelton, Connecticut, USA*
Co-Investigators: ***Nils Ryden*** *and* ***Josefin Starkhammar***, *Norfee Tech, Lund, Sweden*
Administrative Staff: ***Jin Park***, *Park Seismic LLC, Shelton, Connecticut, USA*

SUMMARY

- Automatic evaluation of the shear-wave velocity (Vs) and thickness (H) of a HMA pavement is the ultimate goal of this project, especially for the "In-Field" operation of the final system.
- Two methods (Methods I & II) are invented that can evaluate Vs and H in a fully automated manner by directly overlapping a modeled Lamb dispersion curve (A0) on top of the measured dispersion image.
- However, before the method is applied, the dispersion images must be properly prepared so that they have the maximum signal-to-noise ratio (S/N) by enhancing the signal Lamb-wave (A0) trend, while suppressing all other noise trends. One raw seismic record obtained from one impact at a specific location on the pavement contains not only the signal Lamb-surface waves, but also random noise waves generated from both subsurface (e.g., body waves and scattered surface waves) and surface (e.g., wind, ambient vibrations, side scattering, etc.). The former type of waves should be fairly consistent in dispersion trend from one location to another as the pavement conditions (i.e., velocity and thickness) do not change abruptly, while the latter type of noise waves may change rather abruptly and randomly, contributing to the significant inconsistency in the measured dispersion images. This harmful effect can be significantly reduced by stacking ambient dispersion images so that the relatively coherent dispersion trend can be amplified through the constructive interference, while the random noise trends can be suppressed through the destructive interference. The two methods (I & II) overlap a modeled curve (A0) on top of the stacked dispersion image to evaluate velocity (Vs) and thickness (H) automatically without any operator's involvement.
- The Method I first attempts to evaluate the phase velocity (Vphs) of the asymptotic trend of Lamb dispersion trend (A0) at the high frequency (e.g., > 20 kHz) and takes it as surface wave velocity (VR) of the pavement, which is about 93% of shear velocity (Vs) at Poisson's ratio of 0.3 (i.e., $VR \approx 0.93Vs$ @ POS = 0.3). This gives $Vs \approx 1.07 \times VR$. And then, theoretical A0 curves are modeled for different pavement thicknesses (H's) (e.g., $5 \text{ cm} \le H \le 25 \text{ cm}$ with 0.1 cm increment) for the given Vs and POS values. For all data points of a given A0 curve, the amplitudes in the dispersion image are summed and normalized with respect to the number of summed data points. Finally, the thickness that results in the highest value of summed amplitude is taken as the evaluated optimum thickness (H-opt).

SUMMARY (Cont'd)

- The Method II repeats the previous process (Method I) of evaluating the optimum thickness (H-opt) for a given velocity (Vs) for different velocities (Vs's). Then, the pair of Vs and H that gives the highest value of summed amplitude on the dispersion image is taken as the evaluated optimum pair of Vs and H (i.e., Vs-opt and H-opt). The testing velocity range (i.e., Vs-min ≤ Vs ≤ Vs-max) can be chosen as a certain ratio of the velocity (Vs-asm) determined from the asymptotic trend of dispersion image previously outlined; for example, Vs-min = 0.75 x Vs-asm and Vs-max = 1.25 x Vs-asm. The testing can proceed with a small velocity increment (e.g., dVs = 10 m/s).
- A layer model is created to represent a typical HMA layer underlain by a base layer and then natural soil/weathered rock. A 48-channel seismic record is modeled by using this layer model through the reflectivity method. The modeled seismic record is then processed to generate a dispersion image. Aforementioned two methods (I & II) are then tested on this dispersion image and their results are compared.
- From this test, velocities (Vs's) evaluated from the two methods are similar within 1.5% difference. The Vs from Method I is more accurate (0.3% error) than that from Method II (1.9% error). Thicknesses (H's) from the two methods are similar within 15% difference. The H from Method II is more accurate (5% error) than that from Method I (20% error). Average errors of the two methods are 1.1% in velocity (Vs) and 12.5% in thickness (H), indicating Vs evaluation is a lot more accurate than the H evaluation. The more accurate Vs evaluation (Method I) yielded the higher S/N (0.998) than the other evaluation (Method II) did (0.982). The more accurate H evaluation (Method II) also yielded the higher S/N (0.982) than the other evaluation (Method I) did (0.964). This means the S/N can be a reliable indicator of the accuracy in the evaluated values of both velocity (Vs) and thickness (H). It seems this comparative evaluation has to be further tested on more modeling data sets in the future for different velocities (Vs's) and thicknesses (H's).
- A field data set obtained on September 1, 2019, over a test road was used to test the two methods of evaluating the velocity (Vs) and thickness (H) of pavement. The data set includes seismic measurements at 100 consecutive points along the road (approximately 100-m long distance) by using a field approach presented here. The values of velocities (Vs's) from the two methods (I & II) fall within a reasonable range of HMA layer (e.g., 1300 m/s ≤ Vs ≤ 1500 m/s). The overall trend is quite smooth, indicating measured values from both methods are realistic. Velocities (Vs's) from both methods are similar approximately within 1.0% difference.

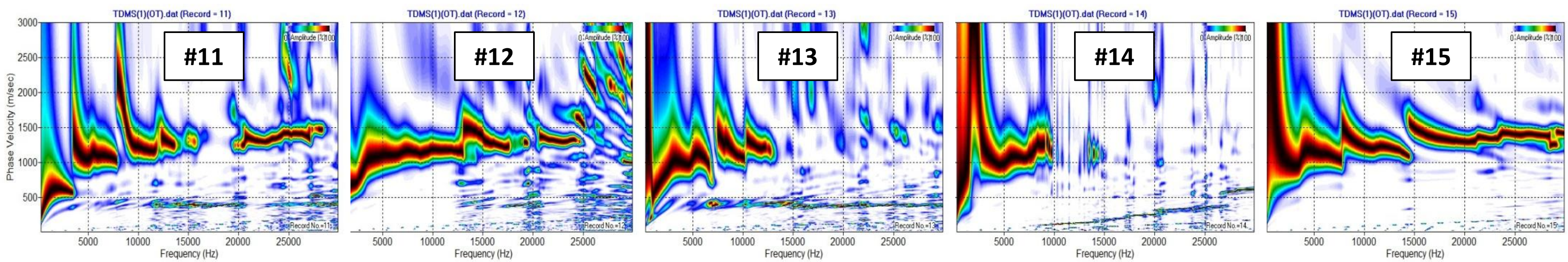
SUMMARY (Cont'd)

- The Vs's from Method II are slightly higher than those from Method I (approximately by 1%). The S/N values from Method II, however, are significantly higher approximately by 5%. In consequence, Vs's from Method II are believed to be more accurate. On the other hand, thicknesses (H's) evaluated from the two methods are different approximately by as much as 30% overall. In addition, the changing trends are fairly abrupt and irregular, indicating less realistic trends than those of the velocity (Vs). In consequence, thickness values are much less reliable than the velocity values. The S/N values for H evaluation from the two methods are almost (99%) identical. The H trend from method II, however, seems to be more consistent than that from method I. In this sense, H results from method II are believed to be more reliable, which is consistent with the result from the modeling data.
- The conventional approach of extracting dispersion curves from the dispersion images followed by the Rayleigh-wave inversion to generate a 2D velocity (Vs) cross section has been applied to the same field data set used to test the two methods (I & II). The objective is to compare the result obtained through the conventional, and therefore manual, analysis with the result obtained automatically (Methods I & II).
- One dispersion curve has been extracted from each dispersion image of the field data set ("September 2020" data set). A total of 100 curves have been inverted by using the traditional Rayleigh-wave inversion algorithm that can account for the modal jump and apparent dispersion trend. Results are obtained by using two different layer models during the inversion; i.e., a 2-layer model with a fixed depth of the interface between layer #1 and #2 and a 5-layer model with a variable maximum depth for the half space. Both results are similar in velocity (Vs) and thickness (H) variation trends although the 5-layer result shows a slightly higher overall velocities. Overall thickness (i.e., 5 cm ≤ H ≤ 10 cm) matches better with the results from the Method II. This conventional analysis approach will be included in the "In-Office" mode of the ParkSEIS-HMA software package because this approach cannot be a full-automatic process.

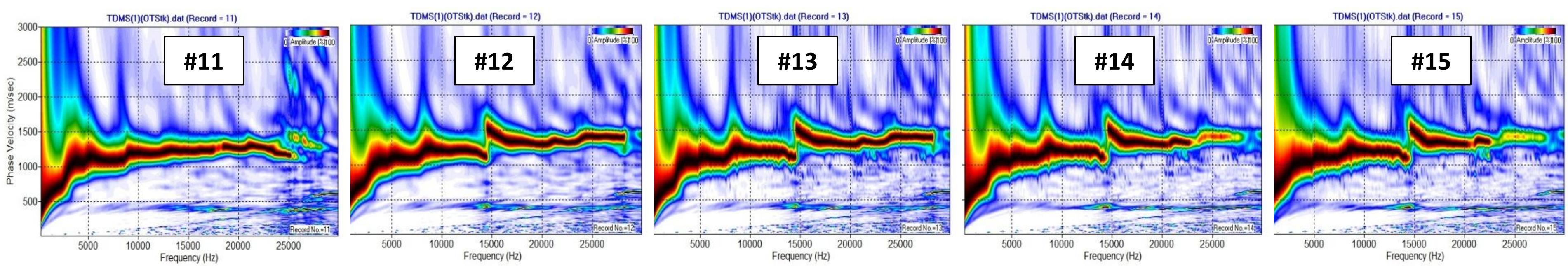
Stacking Ambient Dispersion Images (OT-Stack)

One raw seismic record obtained from one impact at a specific location on the pavement contains not only the signal Lamb-surface waves, but also random noise waves generated from both subsurface (e.g., body waves) and surface (e.g., wind, ambient vibrations, side scattering, etc.). The former type of waves should be fairly consistent in dispersion trend from one location to another as the pavement conditions (i.e., velocity and thickness) do not change abruptly, while the latter type of noise waves may change rather abruptly and randomly, contributing to the significant inconsistency in the processed dispersion images as shown below in the "RAW Dispersion Images." This harmful effect can be significantly reduced by stacking ambient dispersion images so that the relatively coherent dispersion trend can be amplified through the constructive interference, while the random noise trends can be suppressed through the destructive interference as shown below in the "Stacked Dispersion Images," in which four (4) ambient images (i.e., two from the previous and two from the next locations) are stacked on top of the current dispersion image.

RAW Dispersion Images

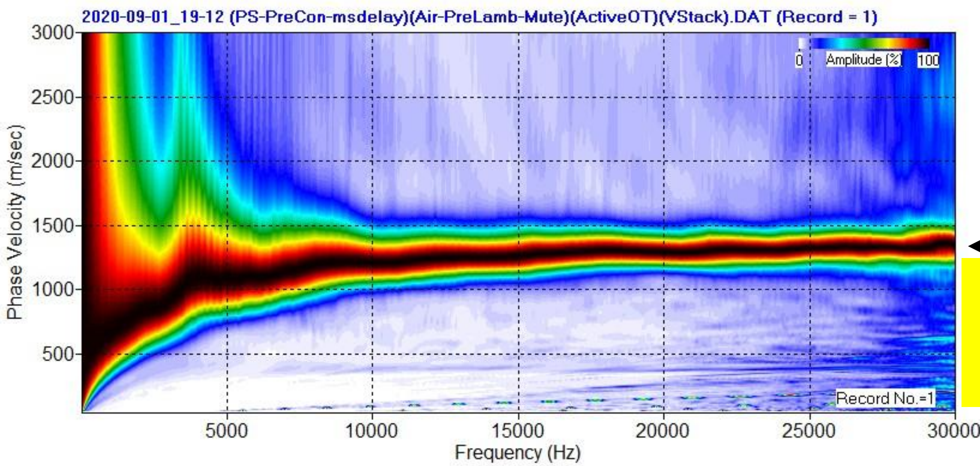


Stacked Dispersion Images



Velocity (Vs) and Thickness (H) Evaluation (Method I)

1. Velocity (Vs) Evaluation (From Asymptotic Trend at the Highest Frequency)

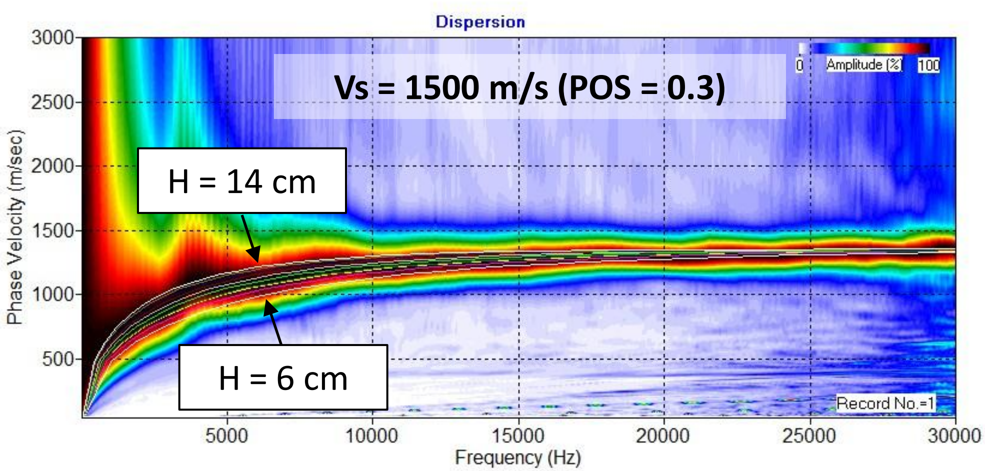


Vphs = 1396 m/s

<u>Vs = 1500 m/s</u>

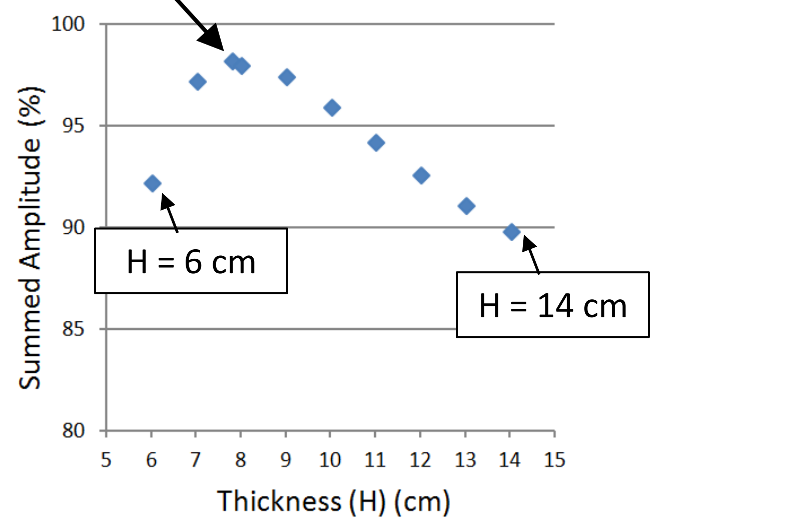
@ POS = 0.3

2. Thickness (H) Scanning (5 cm – 30 cm with 0.1 cm increment)



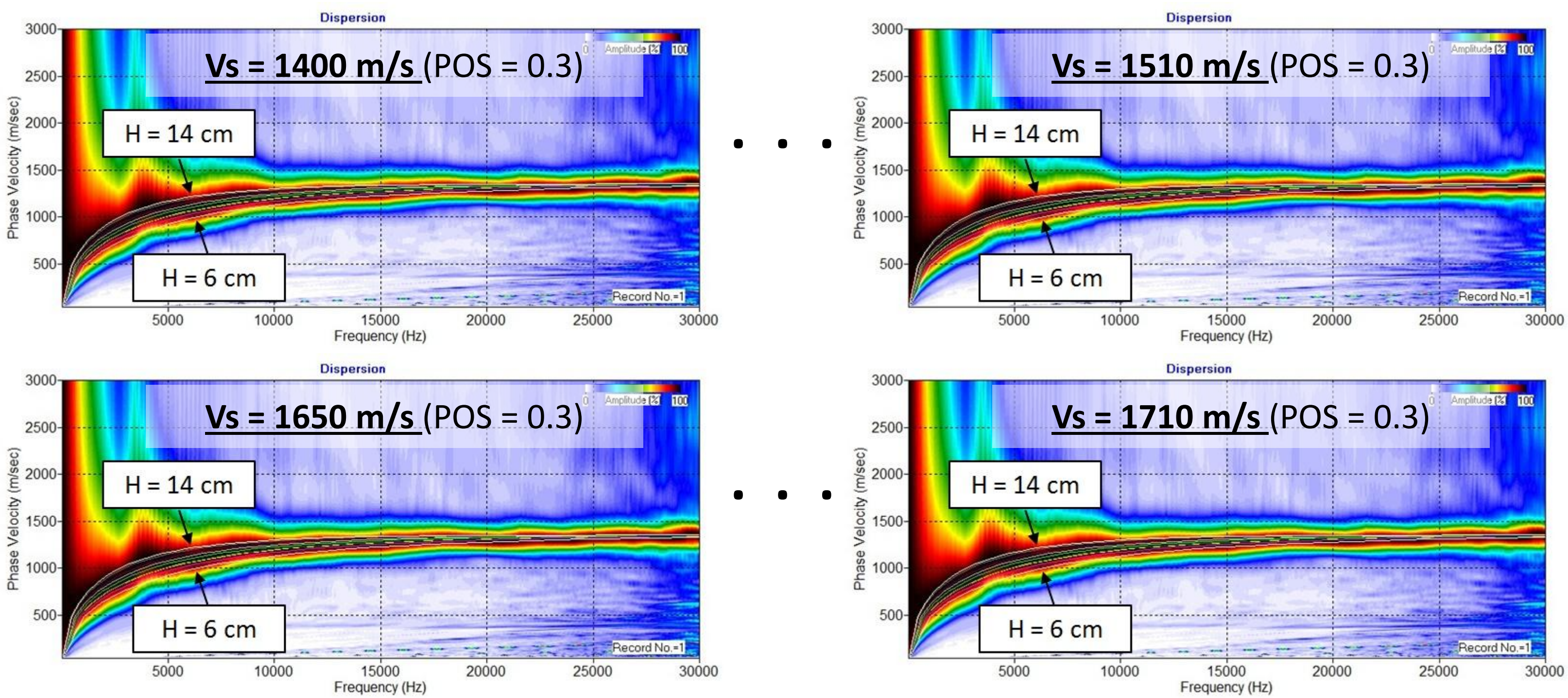
1. The phase velocity (Vphs) of the asymptotic trend of Lamb dispersion trend (A0) at the high frequency (e.g., > 20 kHz) is taken as surface wave velocity (VR) of the pavement, which is about 93% of shear velocity (Vs) at Poisson's ratio of 0.3 (i.e., VR≈0.93Vs @ POS = 0.3). This gives Vs ≈ 1.07 x VR.
2. Theoretical A0 curves are modeled for different pavement thicknesses (H's) (e.g., 5 cm ≤ H ≤ 25 cm with 0.1 cm increment) for the given Vs and POS values. For all data points of a given A0 curve, the amplitudes of dispersion image are summed and normalized with respect to the number of summed data points.
3. The thickness that results in the highest summed amplitude is taken the optimum thickness (H-opt) evaluated as illustrated below (H = 7.8 cm).

<u>H = 7.8 cm</u>



Velocity (Vs) and Thickness (H) Evaluation (Method II)

Previous process of evaluating the optimum thickness (H-opt) by modeling theoretical A0 curves for a given velocity (Vs) is repeated for different velocities (Vs's). The pair of Vs and H that gives the highest summed amplitude on the dispersion image is taken as the optimum pair of Vs and H (i.e., Vs-opt and H-opt). This is illustrated below for a few arbitrary velocities (Vs's). The testing velocity range (i.e., Vs-min and Vs-max) can be chosen as a certain ratio of the Vs-asm determined from the asymptotic trend of dispersion image previously illustrated; for example, Vs-min = 0.75 x Vs-asm and Vs-max = 1.25 x Vs-asm. The testing can proceed with a small velocity increment (e.g., dVs = 10 m/s).

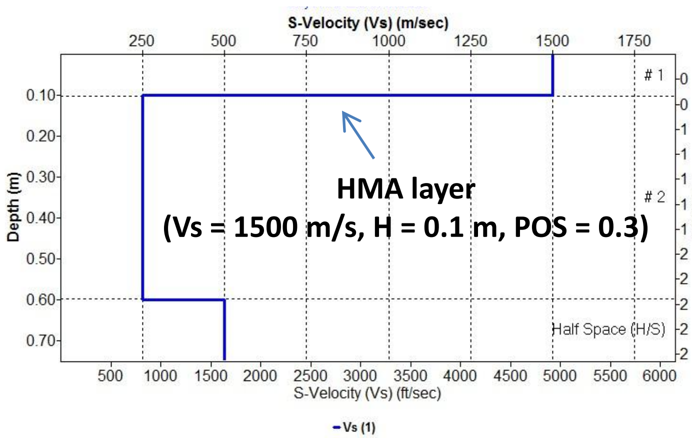


Testing of Two Methods (I & II) on Modeling Data

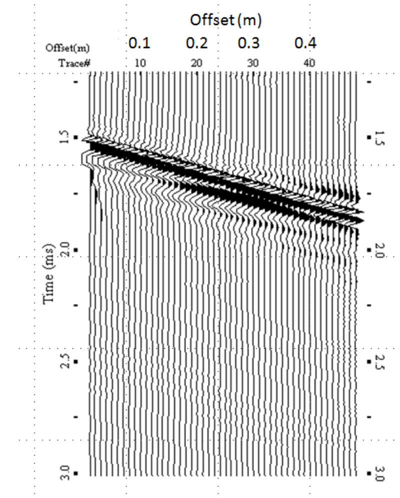
- A layer model is created to represent a typical HMA layer underlain by a base layer and then natural soil/weathered rock.
- A 48-channel seismic record is modeled by using this layer model through the reflectivity modeling method.
- The modeled seismic record is then processed to generate a dispersion image.
- Aforementioned two methods (I & II) are tested on this dispersion image and their results are compared.

Seismic Modeling (Reflectivity Method)

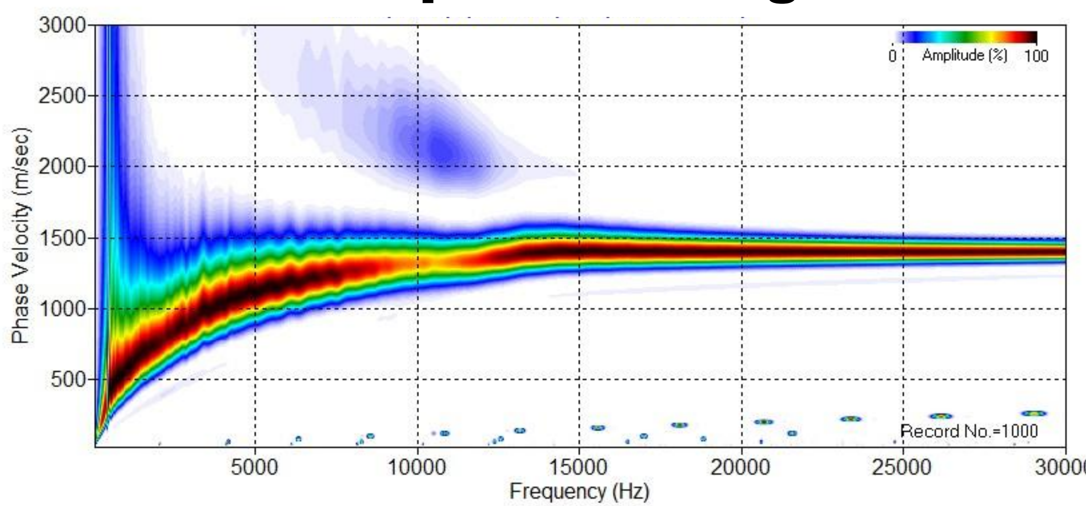
Model (Vs, H, POS, etc.)



Modeled Seismic Data

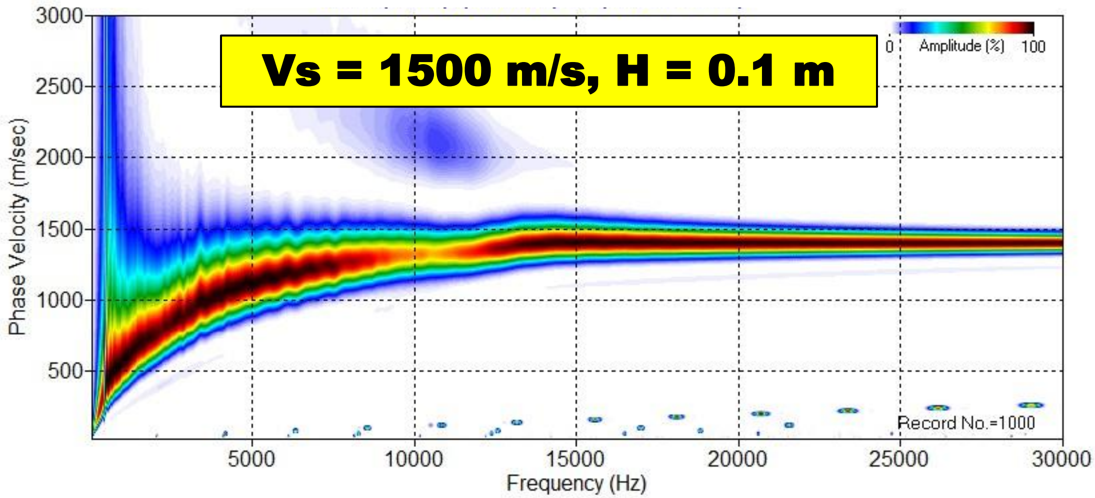


Dispersion Image



Velocity (Vs) and Thickness (H) Evaluation Method I & II

Modeled Dispersion Image



	Velocity (Vs)		Thickness (H)	
	Vs (m/s)	S/N*	**H (m)**	S/N*
Method I	**1504**	0.998	**0.120**	0.964
Method II	**1528**	0.982	**0.105**	0.982

**The normalized signal-to-noise ratio (S/N) represents the summed amplitude of the dispersion image along the modeled A0 curve for the evaluated velocity (Vs) and thickness (H).*

Discussions

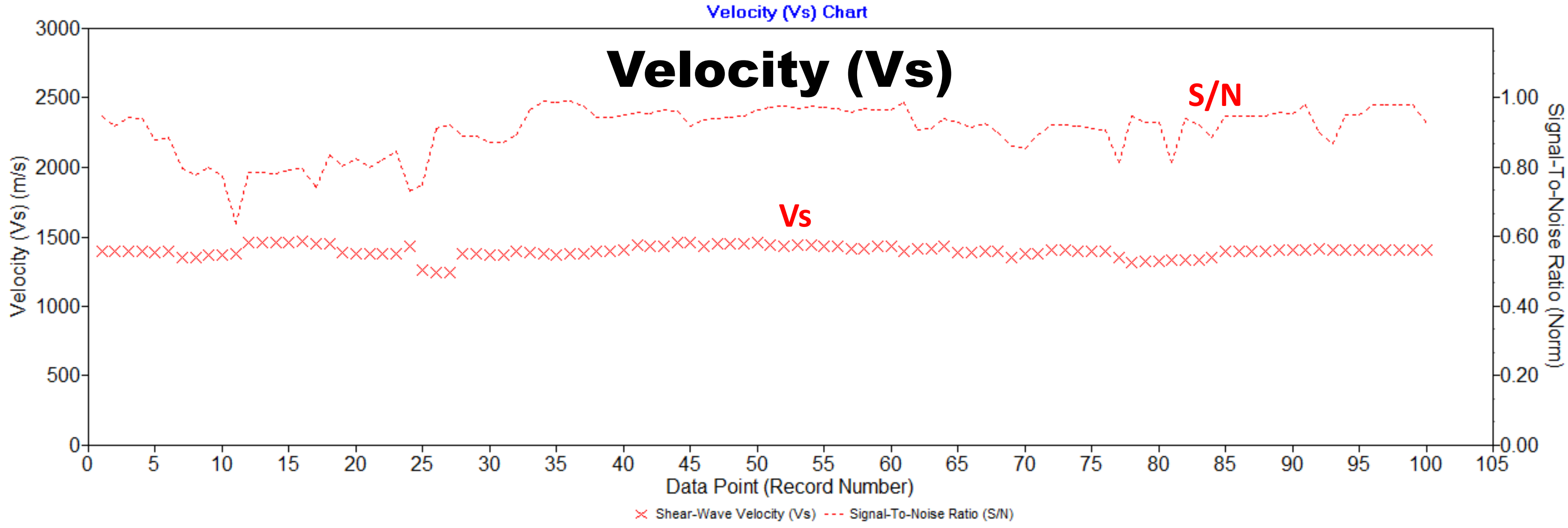
- Velocities (Vs's) from the two methods are similar within 1.5% difference. The Vs from Method I is more accurate (0.3% error) than that from Method II (1.9% error).
- Thicknesses (H's) from the two methods are similar within 15% difference. The H from Method II is more accurate (5% error) than that from Method I (20% error).
- Average errors of the two methods are 1.1% in velocity (Vs) and 12.5% in thickness (H), indicating Vs evaluation is a lot more accurate than the H evaluation.
- The more accurate Vs evaluation (Method I) yielded the higher S/N (0.998) than the other evaluation (Method II) did (0.982). The more accurate H evaluation (Method II) also yielded the higher S/N (0.982) than the other evaluation (Method I) did (0.964).
- This means the S/N can be a reliable indicator of the accuracy in the evaluated values of both velocity (Vs) and thickness (H).
- It seems this comparative evaluation has to be further tested on more modeling data sets in the future.

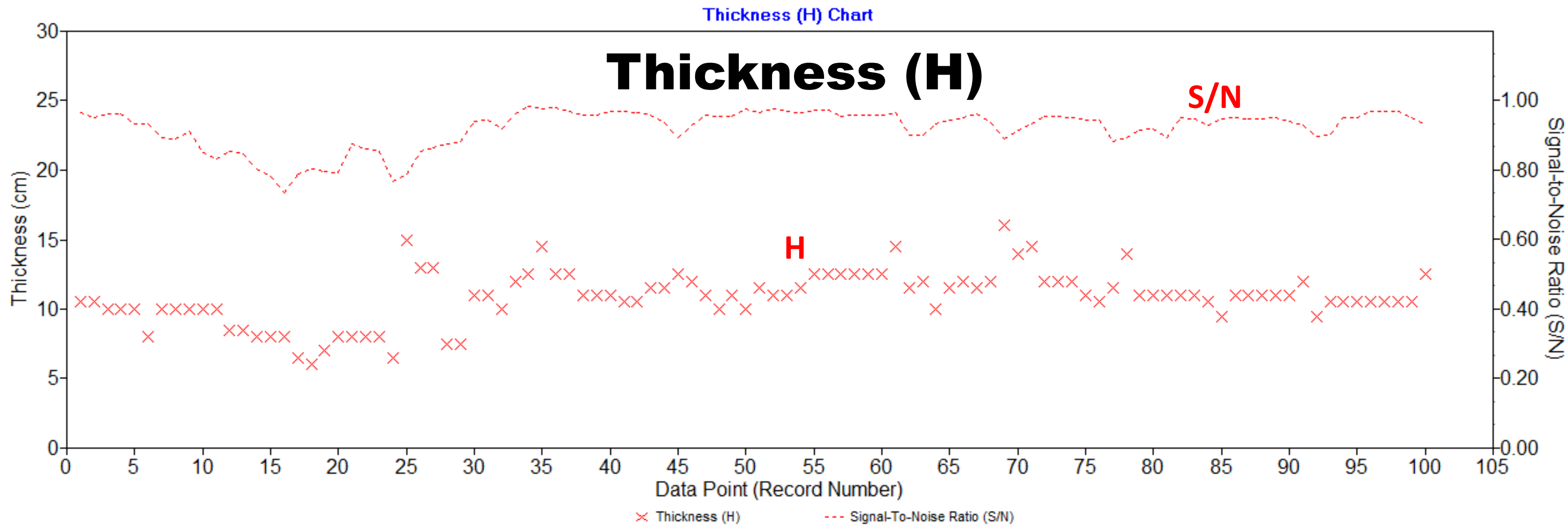
Testing of Two Methods (I & II) on Field Data Set (September 2019)

- A field data set obtained on September 1, 2019, on a test road was used to test the two methods of evaluating the velocity (Vs) and thickness (H) of pavement.
- The data set includes seismic measurements at 100 consecutive points along the road (approximately 100-m long distance) by using the approach presented here.

Method I

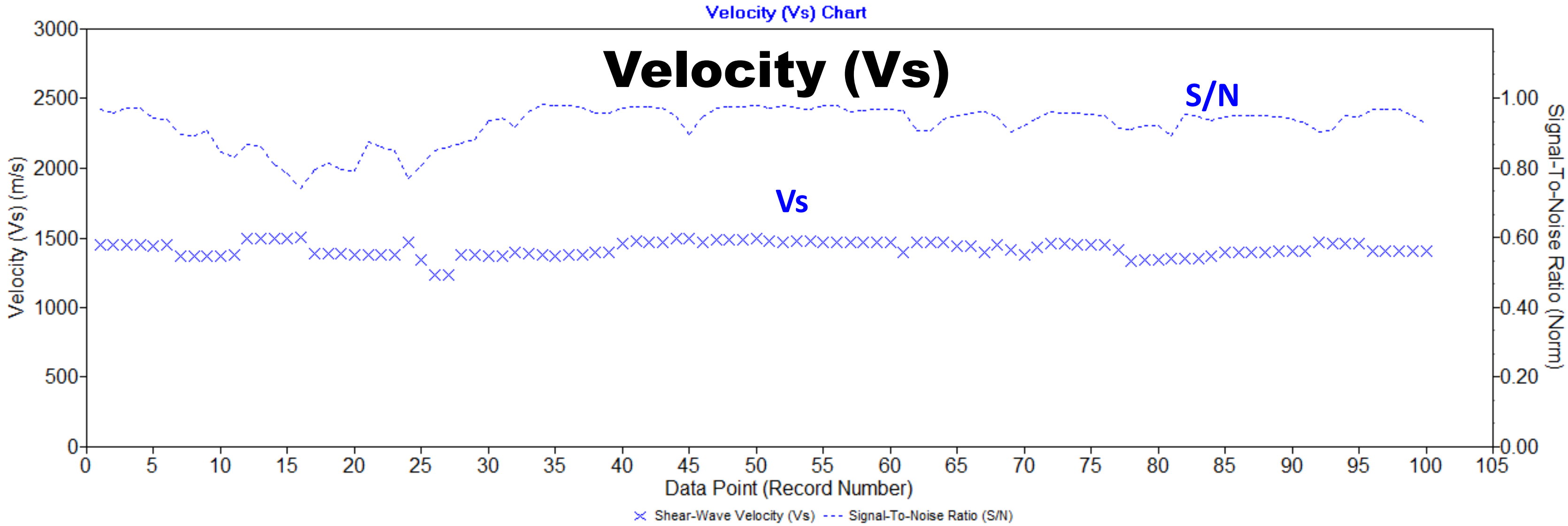
The normalized signal-to-noise ratio represents the summed amplitude of the dispersion image along the modeled A0 curve for the evaluated velocity (Vs) and thickness (H).

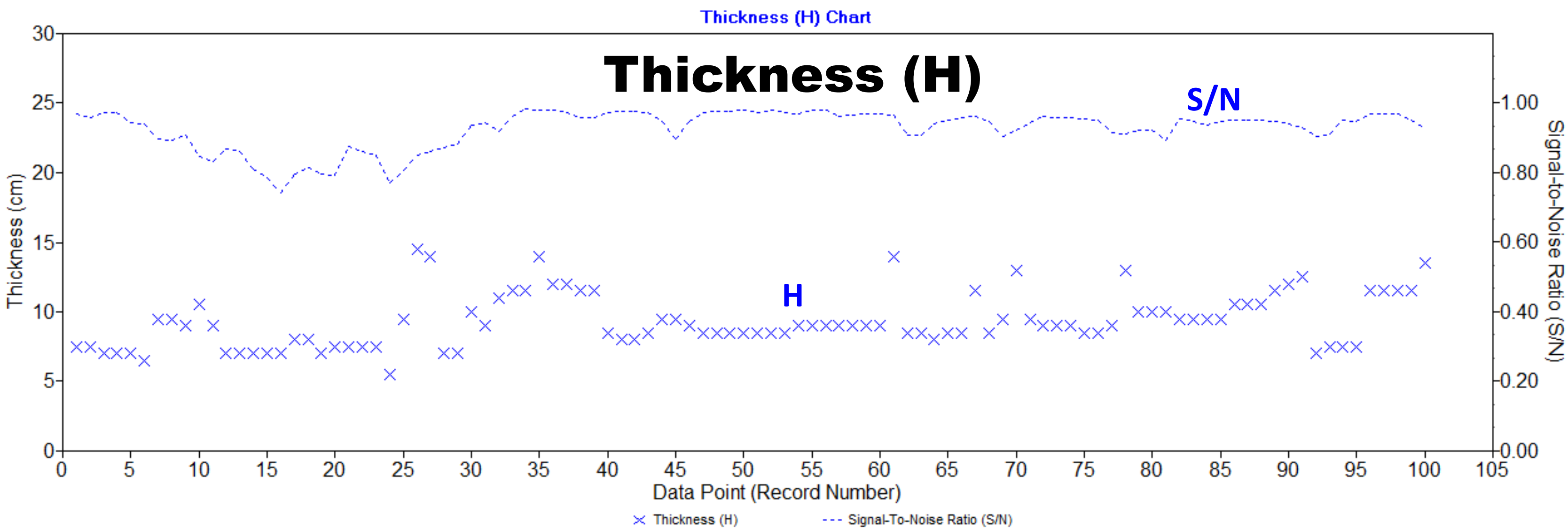




Method II

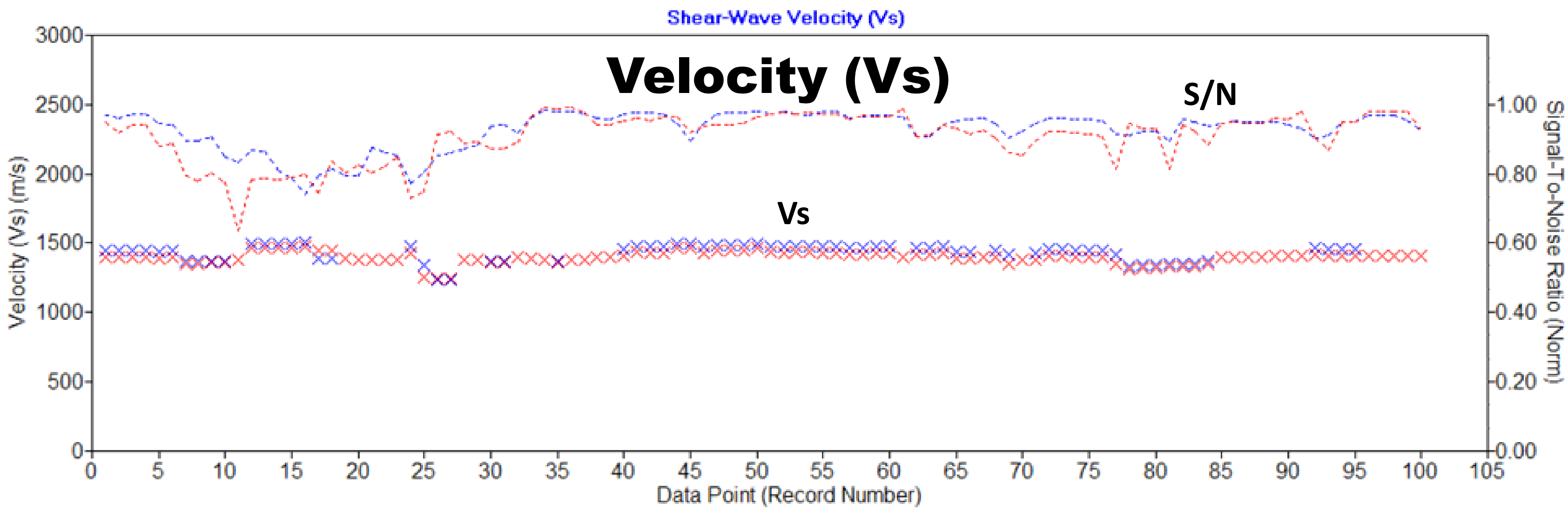
The normalized signal-to-noise ratio represents the summed amplitude of the dispersion image along the modeled A0 curve for the evaluated velocity (Vs) and thickness (H).

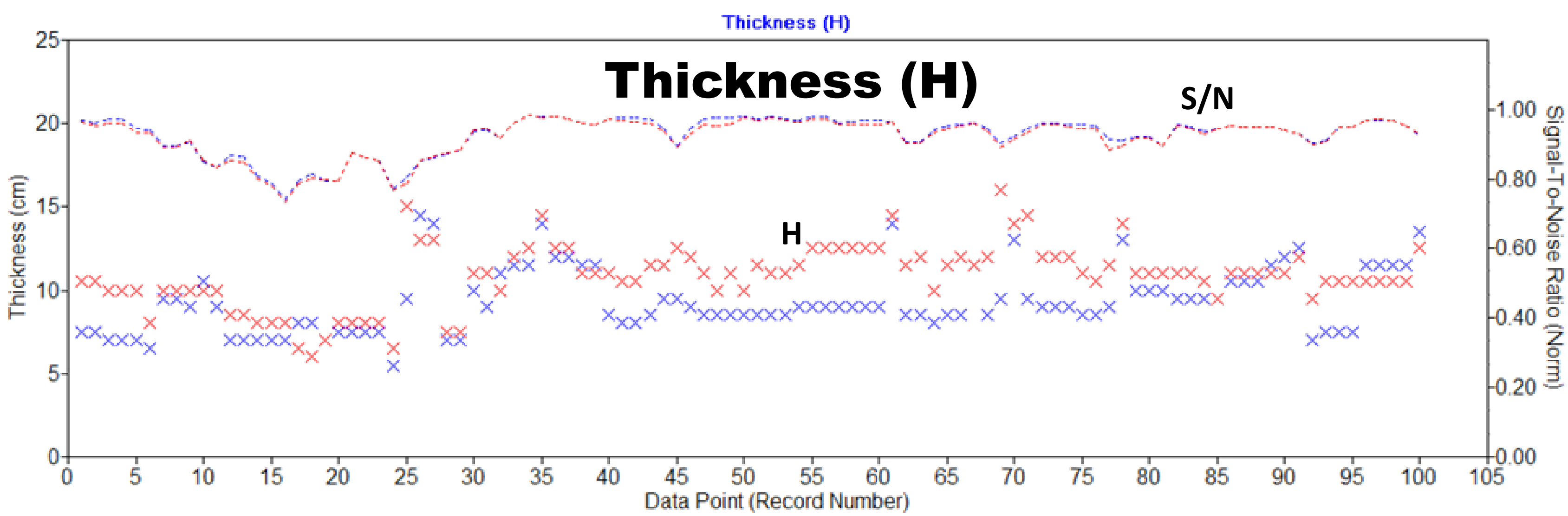




Method I & II

The normalized signal-to-noise ratio represents the summed amplitude of the dispersion image along the modeled A0 curve for the evaluated velocity (Vs) and thickness (H).



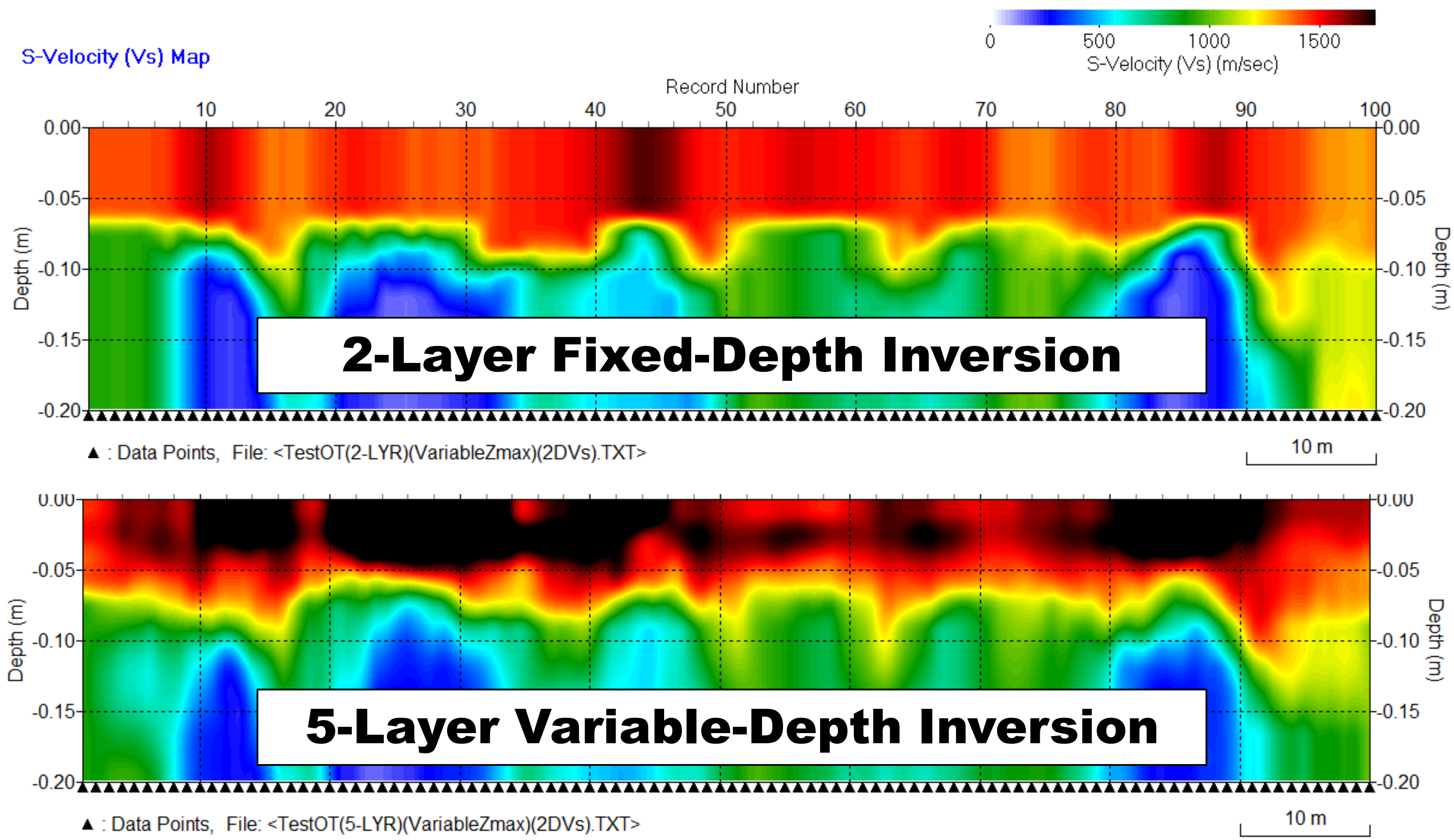


Testing of Conventional (Manual) Analysis on Field Data Set (September 2019)

- The same field data set previously used to test the two automatic methods (I & II) is used for the conventional analysis.
- The main objective is to compare the result obtained through the conventional, and therefore manual, analysis with the result obtained automatically.

Velocity (Vs) Cross Section (Conventional Analysis)

One dispersion curve has been extracted from each dispersion image of the field data set previously used to test the two methods (I & II) ("September 2020" data set). A total of 100 curves have been inverted by using the traditional Rayleigh-wave inversion algorithm that can account for the modal jump and apparent dispersion trend. Results are displayed below for two different layer models used during the inversion; i.e., a 2-layer model with a fixed depth of the interface between layer #1 and #2 (top cross section) and a 5-layer model with a variable maximum depth for the half space (bottom cross section).



Discussions

- Both results from the “2-layer fixed-depth” and “5-layer variable-depth” inversions are similar in velocity (Vs) and thickness (H) variation trends although the 5-layer result show a slightly higher overall velocities.
- Overall thickness (i.e., 5 cm ≤ H ≤ 10 cm) matches better with the results from the automatic method (Method II) previously presented. This conventional analysis approach will be included in the “In-Office” mode of the ParkSEIS-HMA software package because this approach cannot be a full-automatic process.