

HMA Thickness Evaluation (Lamb Curve vs. Impact Echo)

Choon Park, Ph.D.

Park Seismic LLC



Seismic Approach to Quality Management of HMA

MnDOT Contract No. 1034287

Federal Project Number: TPF-5 (341)

Execution: January, 2020 - December, 2021

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

- In theory, thickness of HMA layer (H) can be measured by the same Lamb dispersion curve, the fundamental anti-symmetric (A_0) mode, that is used to evaluate the shear-wave velocity (V_s) of the layer. An A_0 curve consists of a curved part that has increasing phase velocity with frequency and occurs at the low-frequency side of the curve (e.g., 1-10 kHz) and a relatively flat part with a fairly constant phase velocity that occurs at the higher-frequency side of the curve (e.g., 10-50 kHz).
- The constant phase velocity of the curve corresponds to the Rayleigh-wave velocity (V_R) of the HMA layer, which is about 92% of the shear-velocity (V_s) for the common range of Poisson's ratio (e.g., 0.15-0.35). For a given HMA layer of V_R , the onset frequency of the curved part from the flat part of the curve changes with the thickness (H) of the layer; i.e., the thicker layer will result in the lower onset frequency. In consequence, the overall shape of the curved part will also change with H . All these properties of A_0 curve are graphically illustrated in this report.
- Conventional seismic measurements through contact approach (e.g., accelerometer) well depicted both curved and flat parts of A_0 curve. However, the non-contact rolling measurements by using MEMS microphones did not show clear definition of the curved part although they delineated the flat part with superb quality.
- It is believed that this can be closely related to the spectral characteristics of the light impact source that tends to generate more energy at higher frequencies (e.g., 10-50 kHz). This, however, will be verified soon in the near-future when more microphone data sets are collected by using multiple impact sources of different impact energy. However, the phenomenon may also be related to the near-field effect of surface waves as well as attenuation properties of the pavement layer.
- In this report, these two aspects (i.e., near-field effect and attenuation property) are examined by using field data sets acquired in the past by using both contact (i.e., accelerometer + hammer) and non-contact (i.e., microphones + bouncing ball) approaches.

SUMMARY (Cont'd)

- In parallel to the Lamb curve (A0) approach to evaluate the thickness (H), another independent approach that works on the spectral characteristics of the measured seismic wavefields is now considered. It is the Impact Echo (IE) approach that measures the spectral peak that is associated with the seismic resonance within the solid material. The peak occurs at the resonance frequency (f_r) that is determined by the P-wave velocity (V_p) and thickness (H or d) of the layer; i.e., $f_r = \beta V_p / (2d)$ where β (≈ 0.96) is called a correction factor that slightly changes with Poisson's ratio, but is commonly set to a constant value of 0.96.
- First, two different approaches are tested to construct the amplitude spectrum; i.e., stacking individual amplitude spectrum from each channel's data [frequency-domain stacking (FDS)] and stacking all channels seismic data first and then construct the amplitude spectrum [time-domain stacking (TDS)] (Ryden, 2016). It turned out TDS is far more effective than the former.
- Second, the most recent development by Bjurstrom and Ryden (2016) that applies negative phase velocity to construct a frequency-phase velocity spectrum is tested. This approach (Bjurstrom and Ryden, 2016) turned out highly effective and will be used as the main IE method in this project.
- The future plan is to apply both approaches (A0 curve and IE) to evaluate the thickness (H). Then, both values will be used to come up with an average value (H_{ave}) by applying an appropriate weight to each value based on a few quality factors.
- In this report, the general scheme of the IE method is briefly explained. Then, a synthetic seismic record is generated to be used to test each type of IE approach.
- Finally, BR-2016 is used for real data sets from both contact and non-contact approaches.

SUMMARY (Cont'd)

References Cited

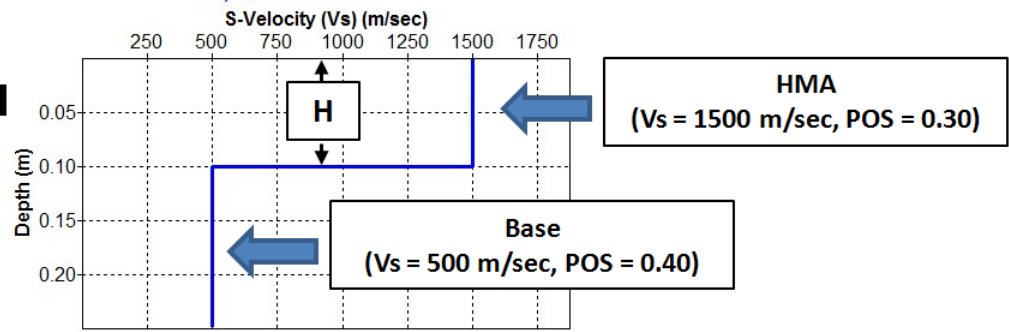
- *Bjurstrom, H., and Ryden, N., 2016, Detecting the thickness mode frequency in a concrete plate using backward wave propagation: J. Acoust. Soc. Am., 139 (2), 649-657.*
- *Ryden, N., 2016, Enhanced impact echo frequency peak by time domain summation of signals with different source receiver spacing: Smart Structures and Systems, vol. 17, no. 1, 59-72.*

Fundamental-Mode Anti-symmetric (A0) Curve

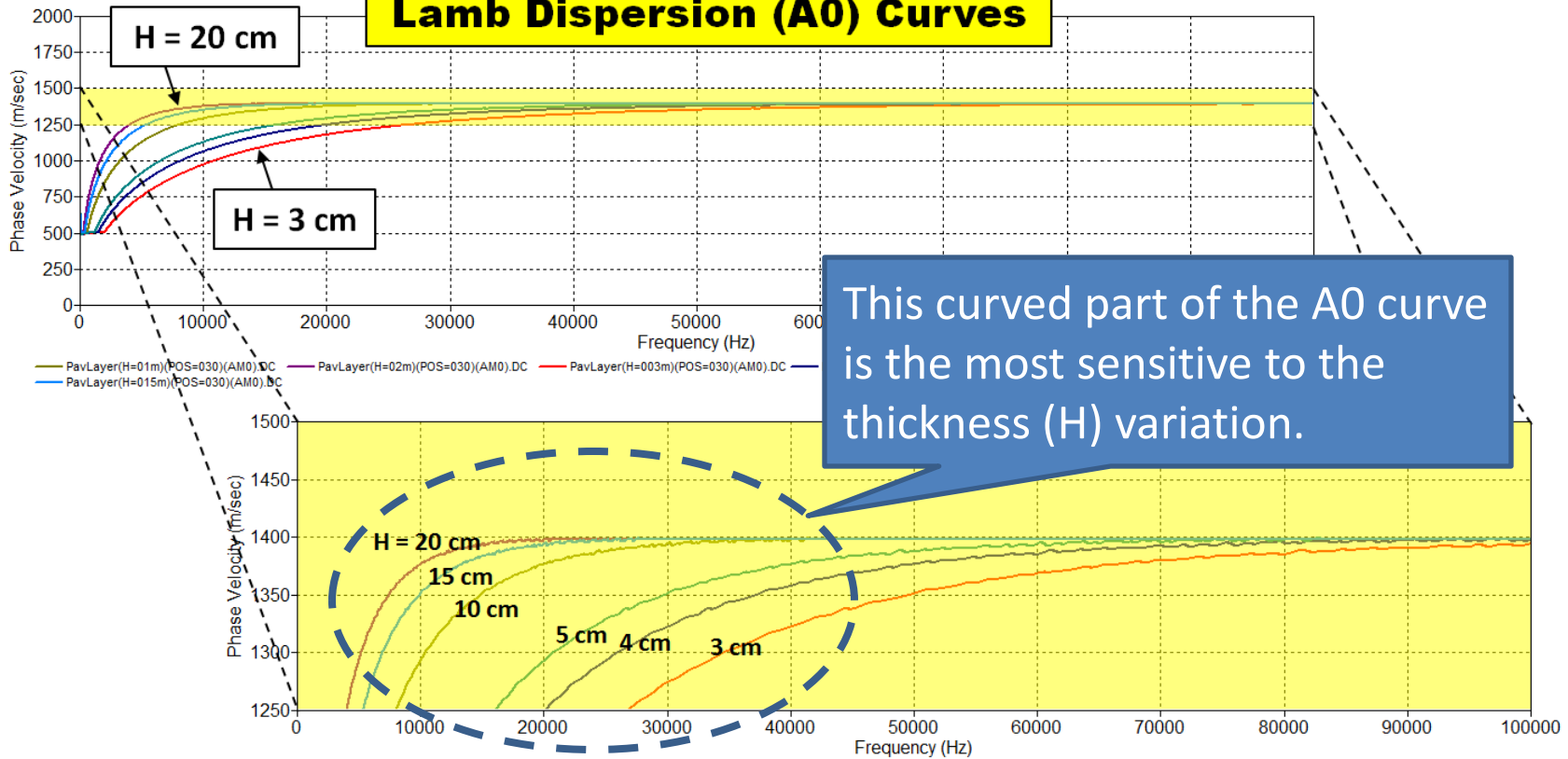
HMA Thickness (H) Model



Layered-Earth Model



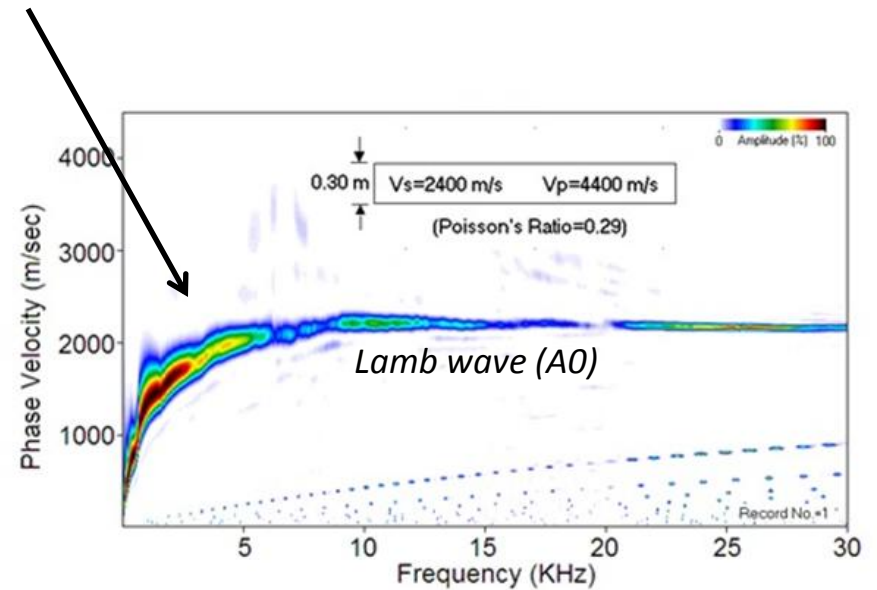
Lamb Dispersion (A0) Curves



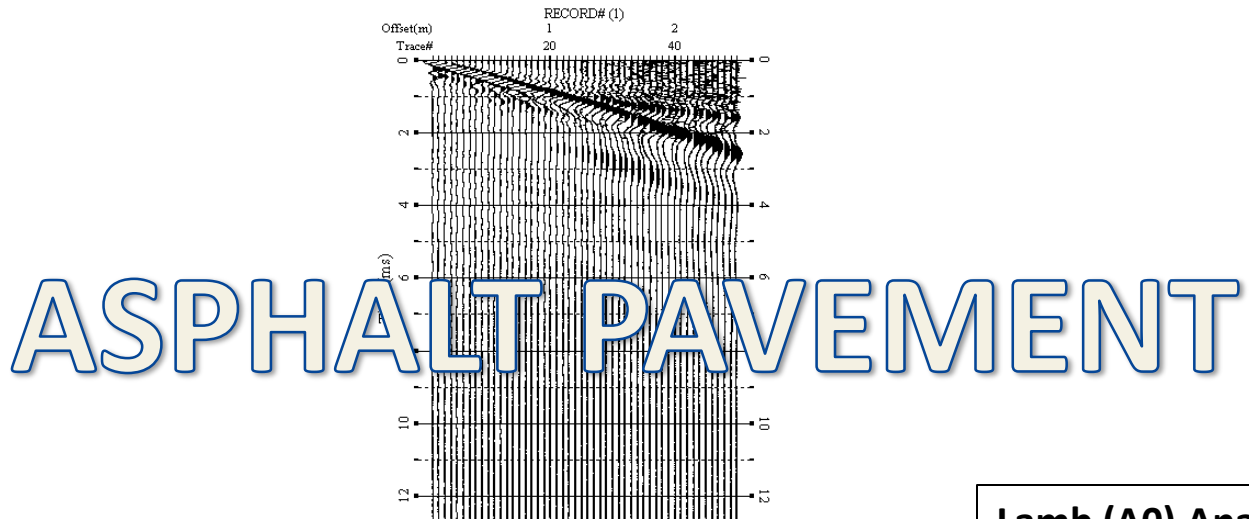
A0 Curve From Contact (Accelerometer) Measurement

Concrete Pavement

Thickness (H) = 0.3 m !!!
(From A0 Analysis)

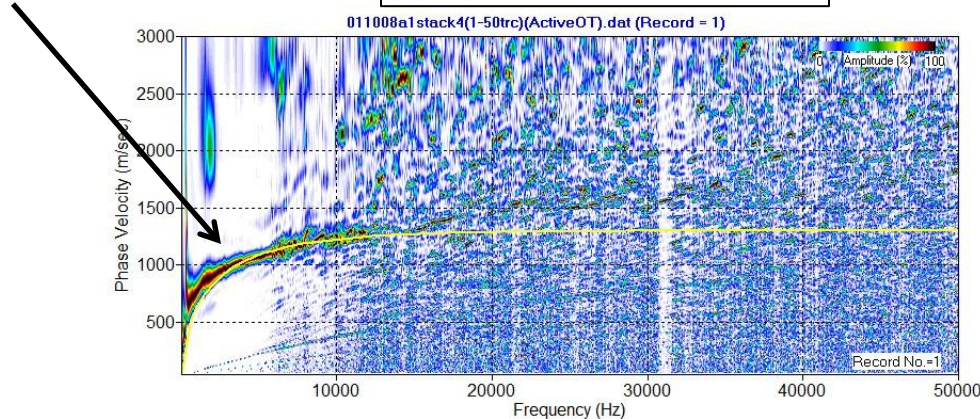
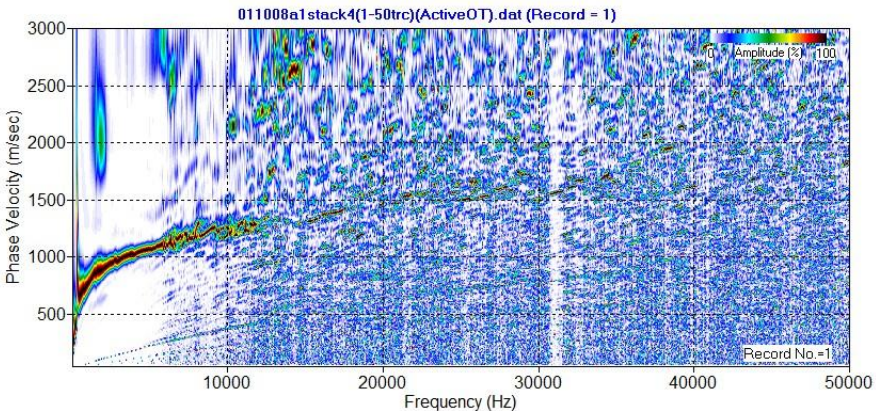


A0 Curve From Contact (Accelerometer) Measurement



Thickness (H) = 0.11 m !!!

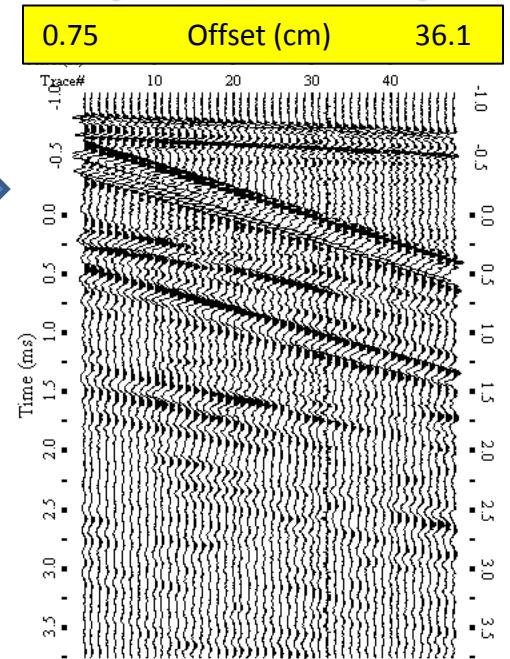
Lamb (A0) Analysis
H = 0.11 m
Vs = 1400 m/s
(POS = 0.3)



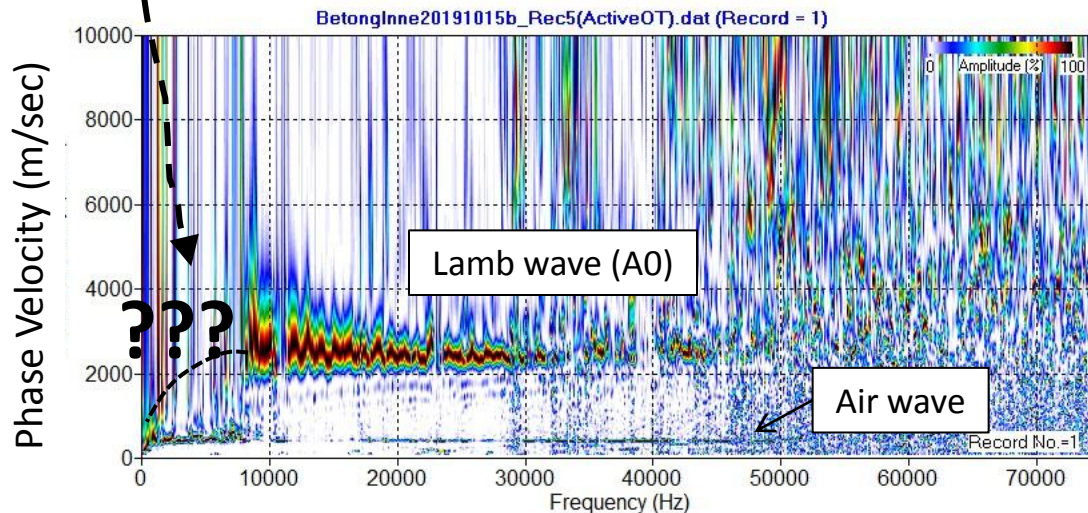
A0 Curve From Non-Contact (Microphone) Measurement* (“Why Low-Frequency Curved Part Missing?”)



Full 48-Channel Record
 ($dx^+ = 0.75$ cm)

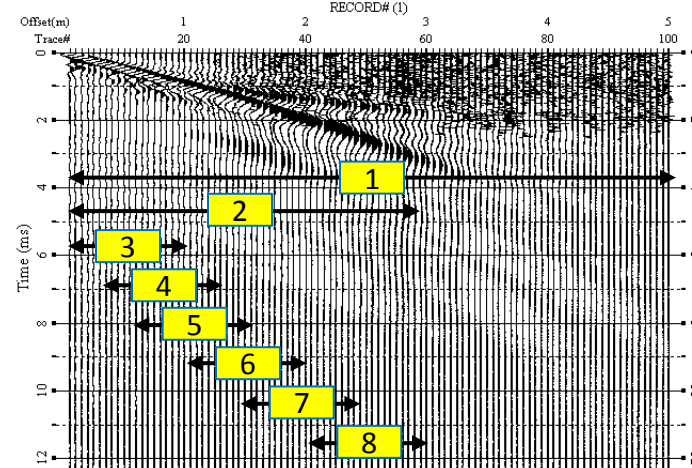


Dispersion Image



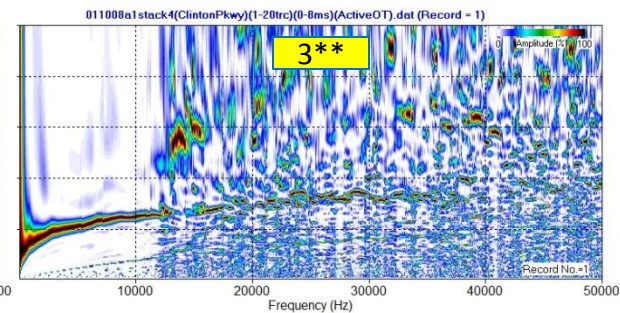
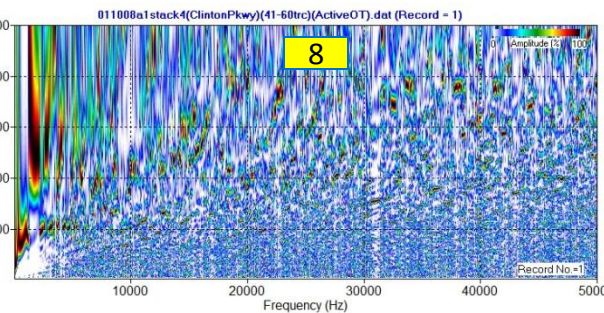
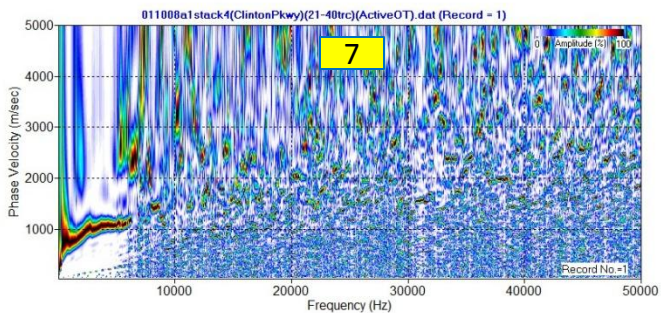
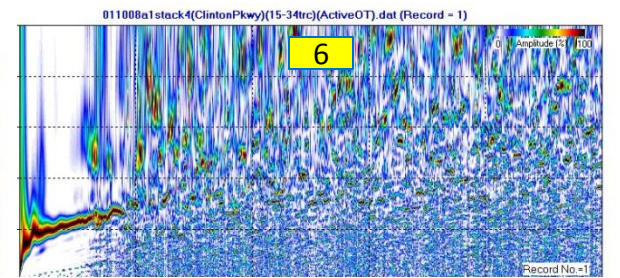
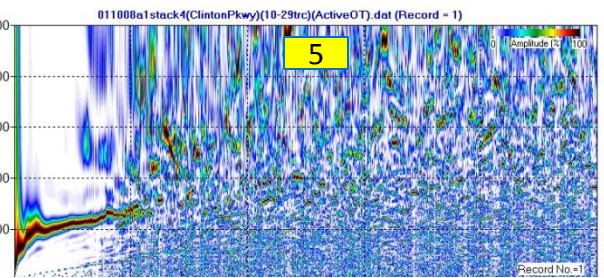
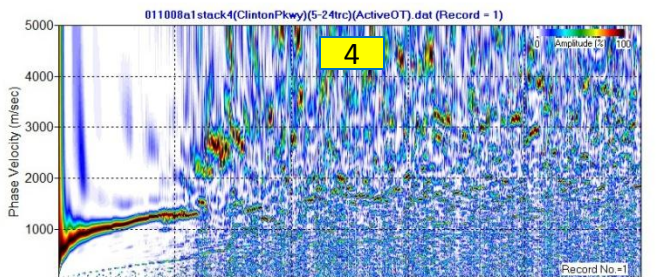
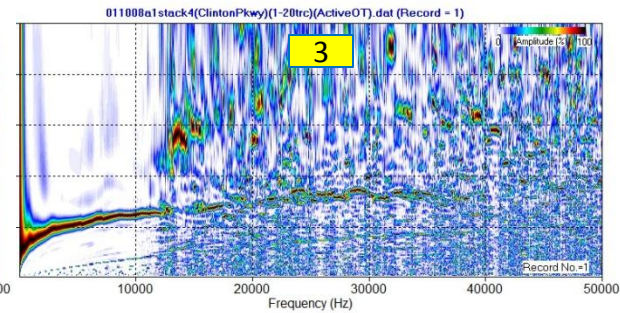
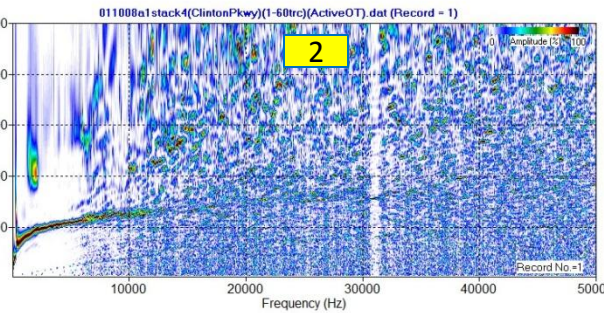
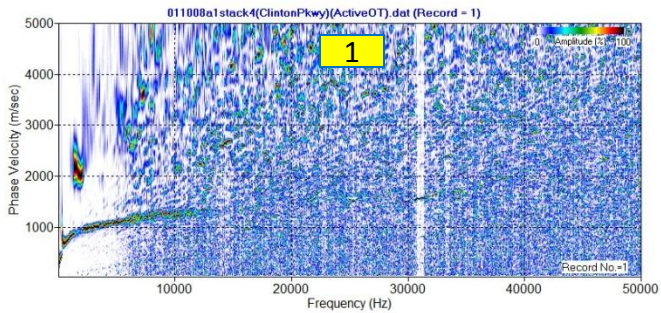
* *Indoor concrete pavement
 (Lund University, Sweden)*
 + *Microphone spacing*

Asphalt* Pavement (Offset and Lamb Dispersion)

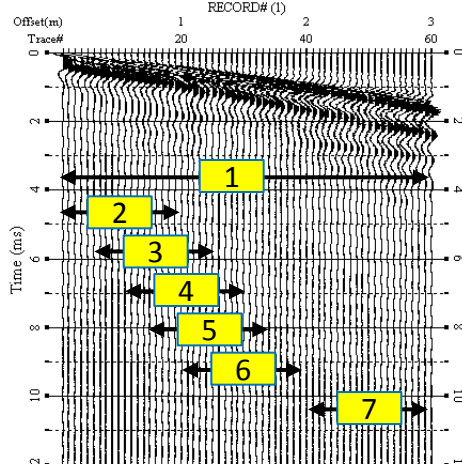


**Accelerometer with a small carpenter hammer (5 cm interval, 0.005-ms sampling interval, and 41 ms recording time)*

***Early part (0.0-8.0 ms) only*

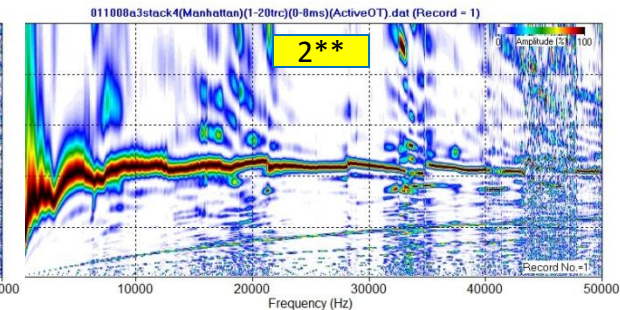
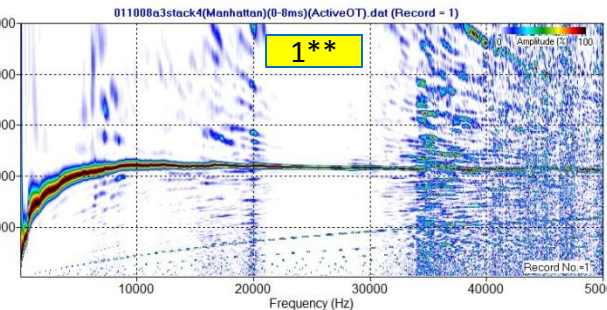
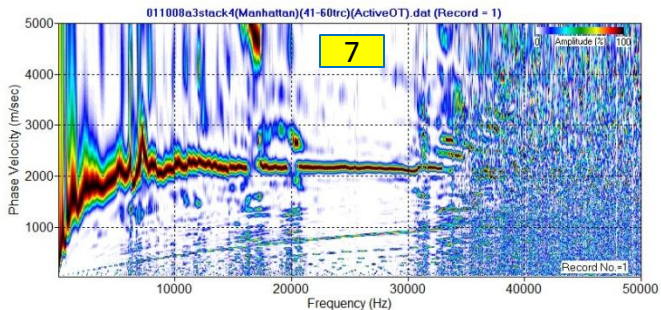
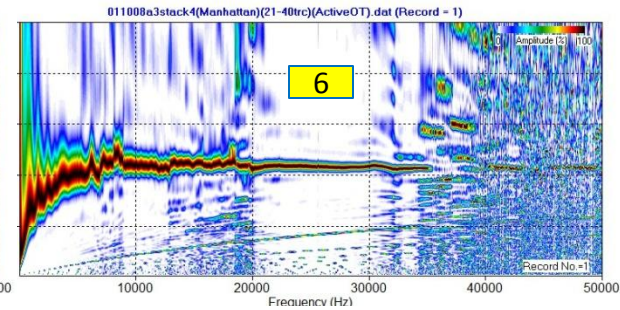
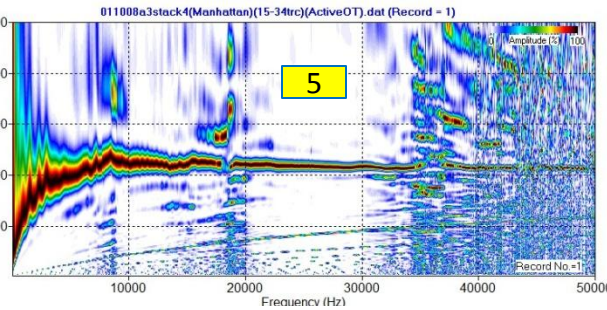
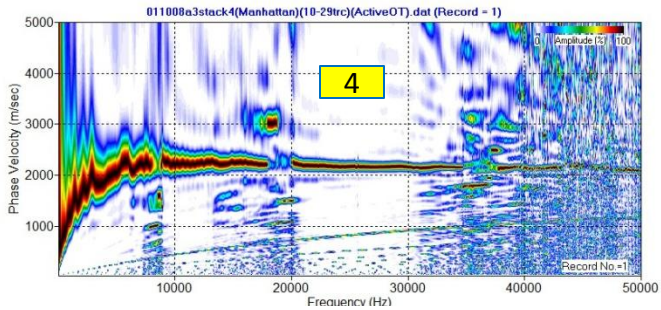
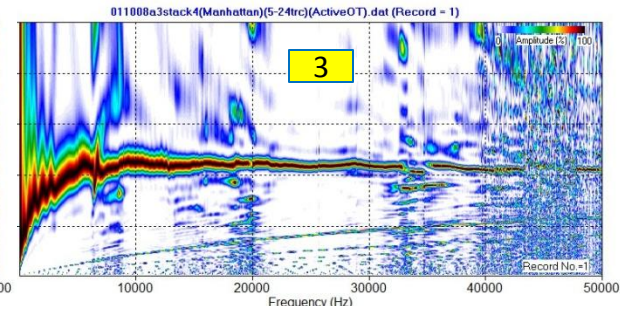
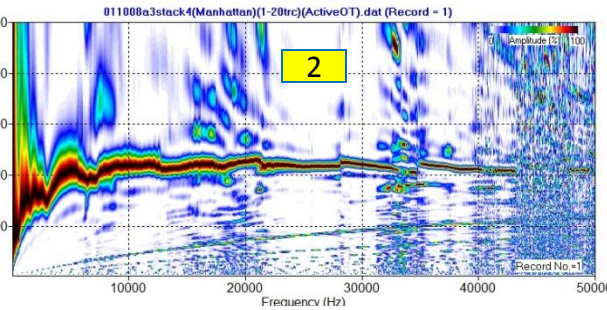
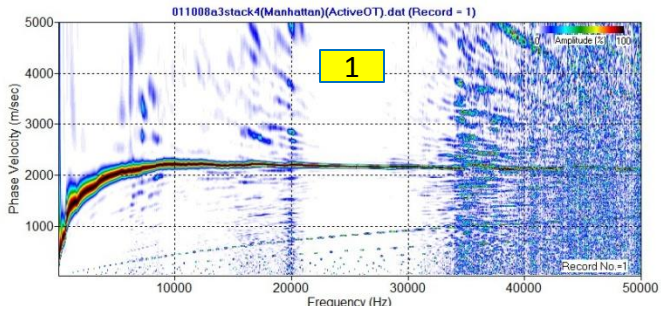


Concrete* Pavement (Offset and Lamb Dispersion)



*Accelerometer with a small
carpenter hammer (5 cm interval, 0.5-
ms sampling interval, and 41 ms
recording time)

**Early part (0.0-8.0) ms only

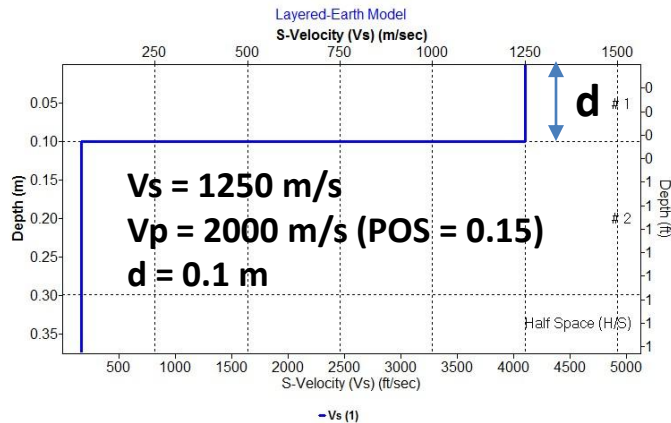


IMPACT ECHO (IE) for Thickness (d) Evaluation

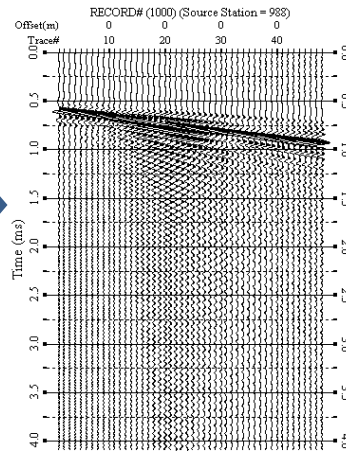
$$f_r = \frac{\beta V_p}{2d} \quad (\beta \approx 0.96)$$

f_r = resonance frequency (Hz)
 V_p = P-wave velocity
 d = thickness (m)
 β = "Correction Factor"

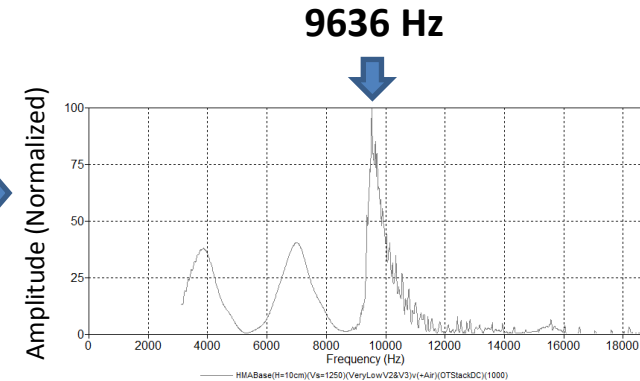
Velocity (Vs & Vp) Model



Modeled Seismic Data



Amplitude Spectrum*



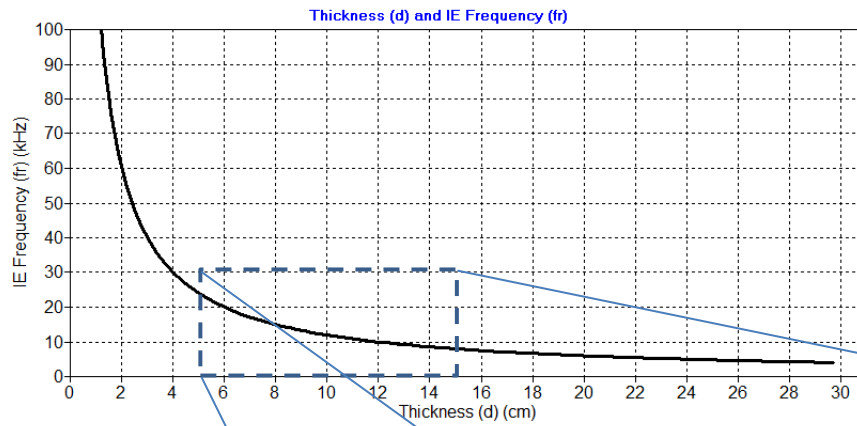
$$d = \frac{\beta V_p}{2f_r} = \frac{0.96 \times 2000}{2 \times 9636} \approx 0.0996 \text{ (m)}$$

**Negative phase velocity stack method (Bjurstrom and Ryden, 2016)*

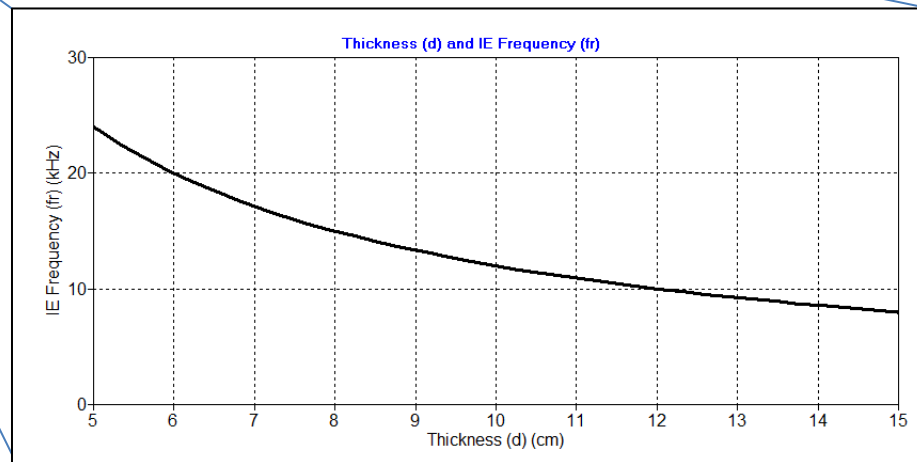
IE f_r – Sensitivity Analysis

For $V_p = 2500$ m/s

d (m)	0.05	0.06	0.10	0.11	0.2	0.21	0.3	0.31
Fr (kHz)	24	20	12	10.9	6.0	5.7	4.0	3.9



f_r for common thickness (d) range
(5 cm – 15 cm)

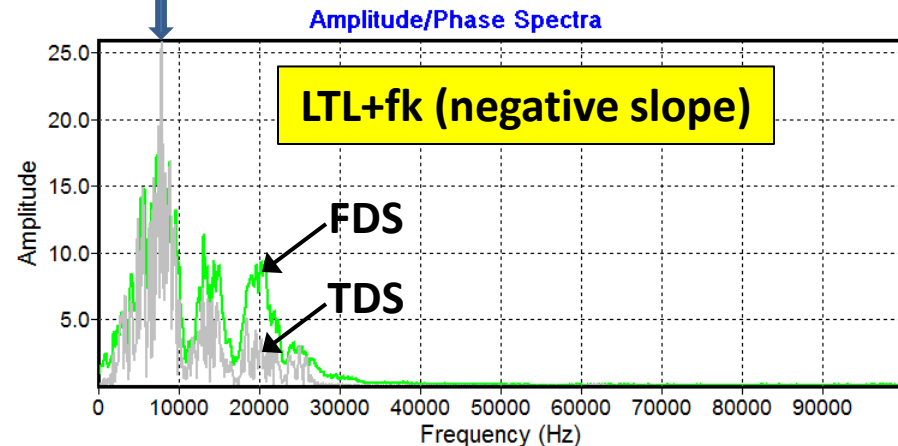
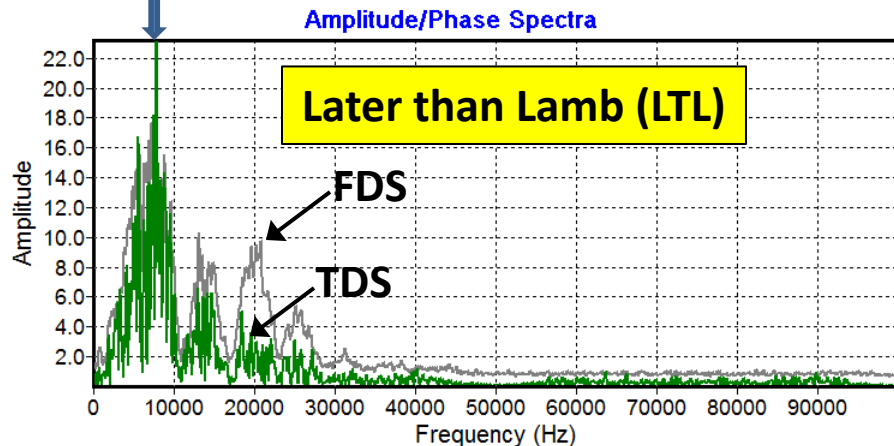
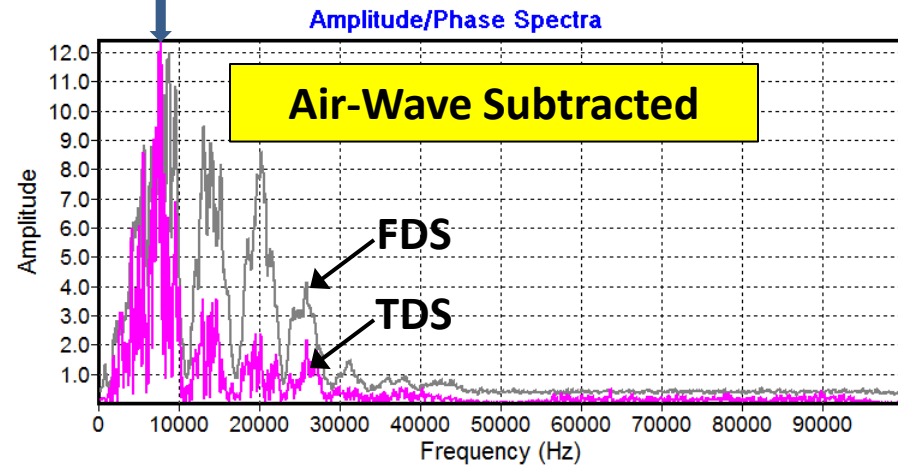
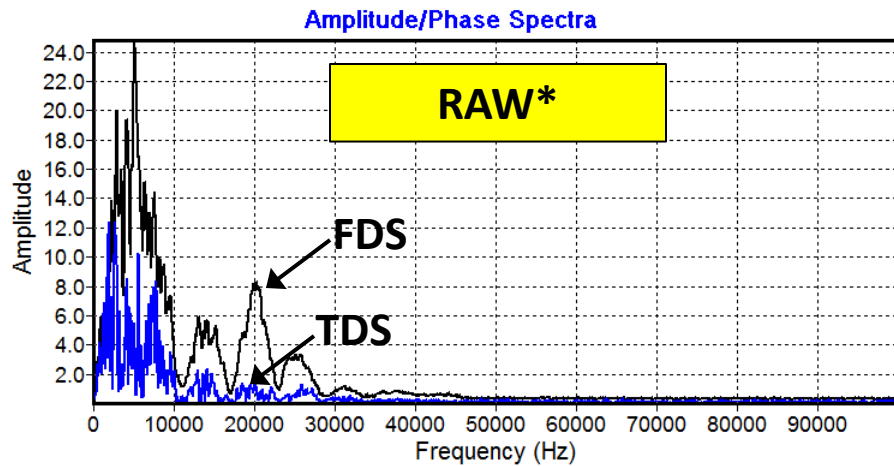


Time-Domain (TDS*) vs. Frequency-Domain (FDS)

Stacking of 48-Channel Field Data**

*Ryden (2016)

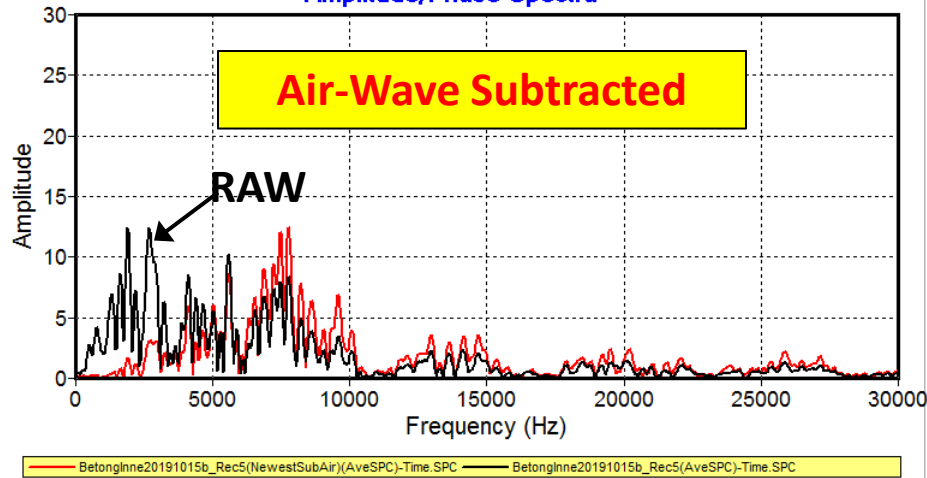
**Non-contact (48-Ch) data from concrete pavement ($H=0.26$ m); $V_s \approx 2600$ m/s, $POS = 0.2$ [from Lamb (A0) analysis].
 f_r is calculated as 7900 Hz.



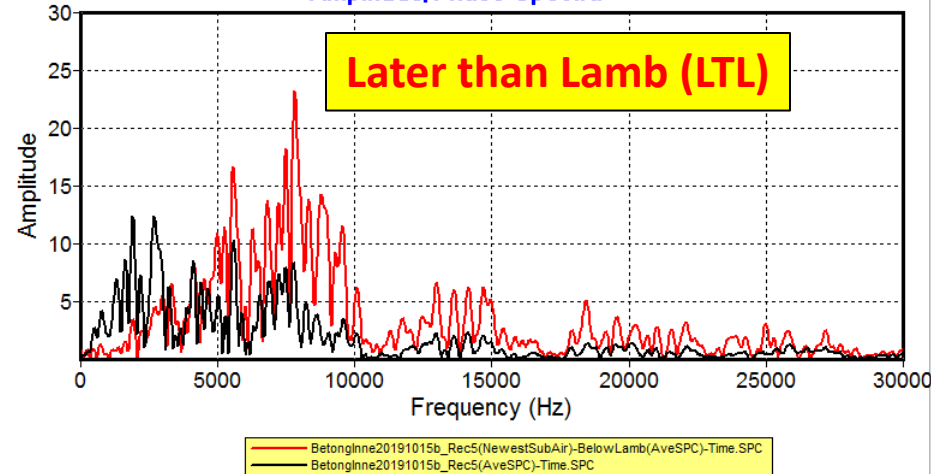
RAW vs. Processed (TDS*)

*Ryden (2016)

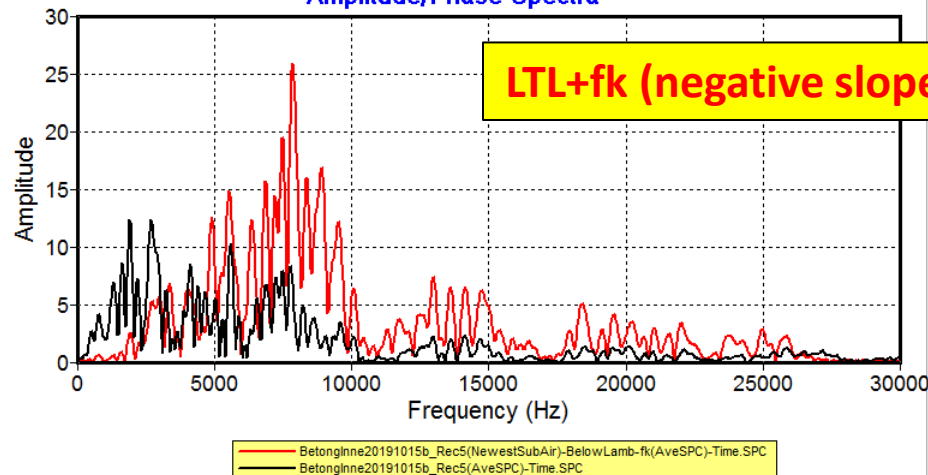
Amplitude/Phase Spectra



Amplitude/Phase Spectra



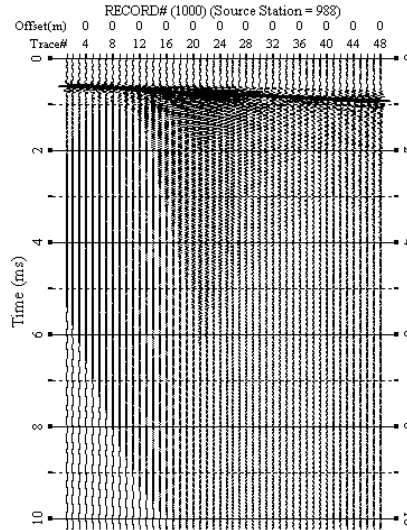
Amplitude/Phase Spectra



IE – Negative Phase-Velocity Stack (NPVS) Method*

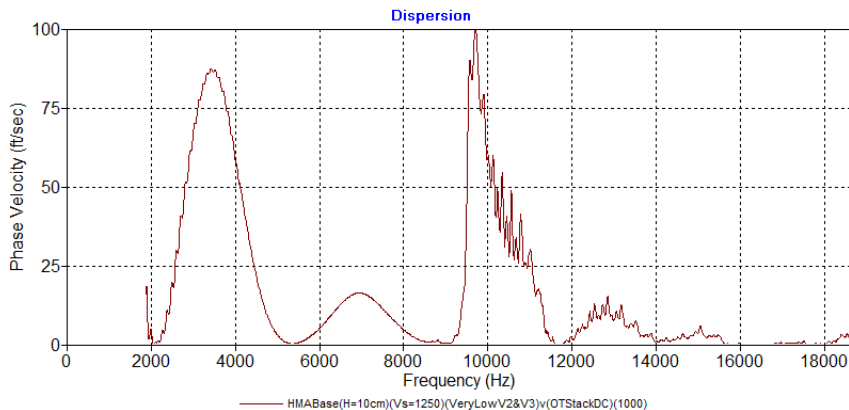
Modeled Seismic Data (MSD)

- * *Bjurstrom and Ryden (2016)*
- ** *Observed peak frequency (fr) and calculated thickness (d)*
- *** *Phase velocity range used for NPVS method: MIN, MAX, and INC.*

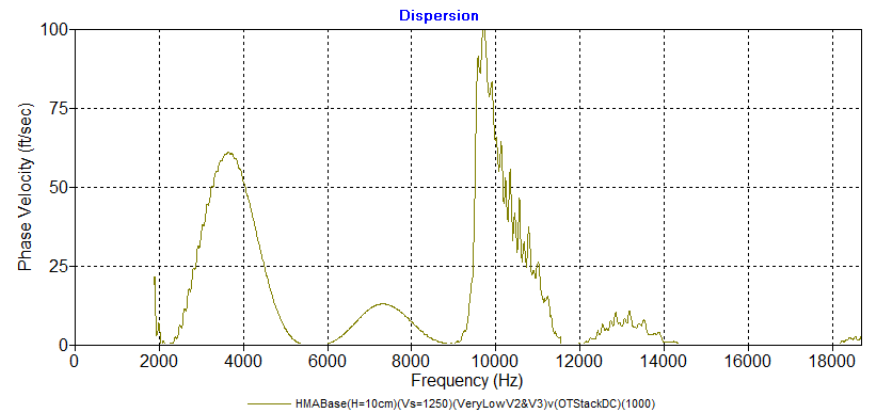


$V_s = 1250 \text{ m/s}$
 $V_p = 2000 \text{ m/s (POS = 0.15)}$
 $d = 0.1 \text{ m}$

$d = 0.096 \text{ m @ } 9700 \text{ Hz}^{**}$
 $(\text{PHS: } -50000, -25000, 1000)^{***}$

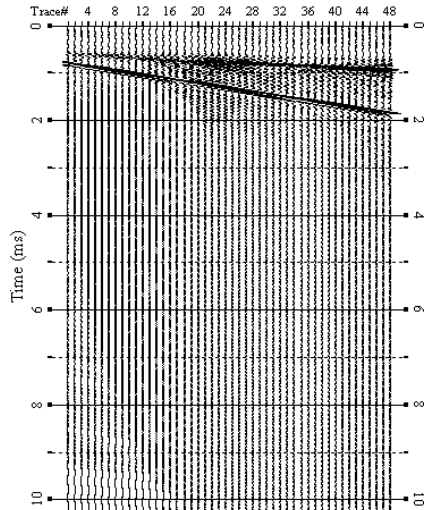


$d = 0.096 \text{ m @ } 9700 \text{ Hz}^{**}$
 $(\text{PHS: } -50000, -45000, 1000)^{***}$

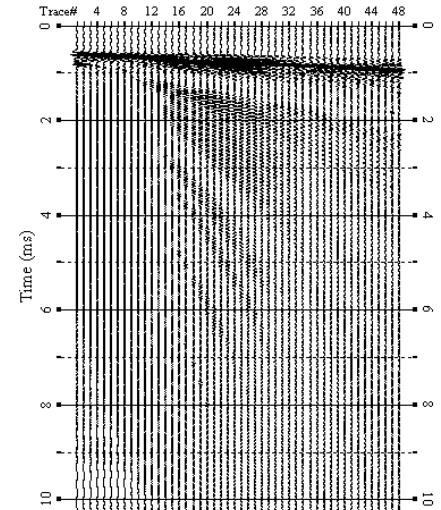


IE* – Air-Wave Added vs. Subtracted

**Modeled Seismic Data (MSD+Air)
(Air-Wave Added)**

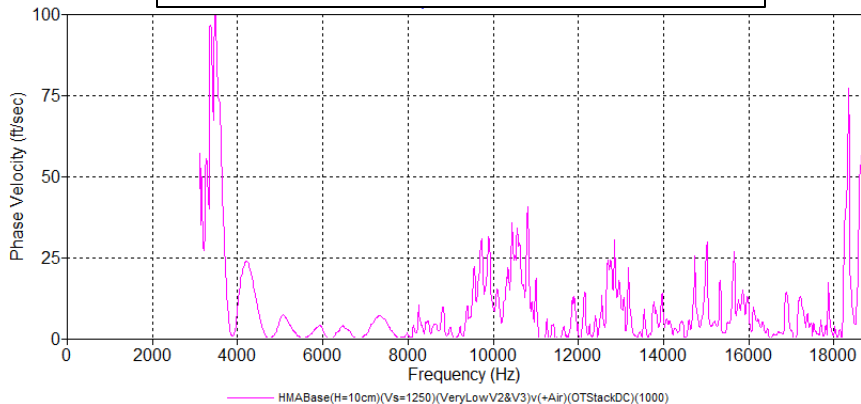


**MSD+Air-Sub
(Air-Wave Subtracted+)**

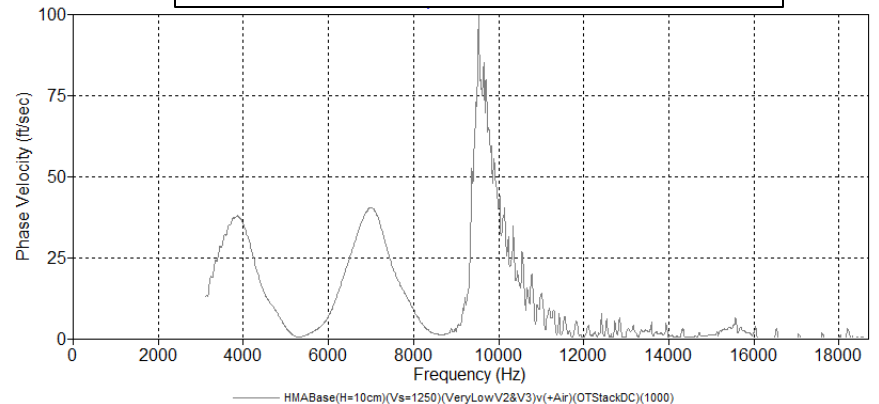


- * *Bjurstrom and Ryden (2016)*
- ** *Observed peak frequency (f_r) and calculated thickness (d)*
- + *Air wave subtracted by using the [moving-window LMO stack](#).*

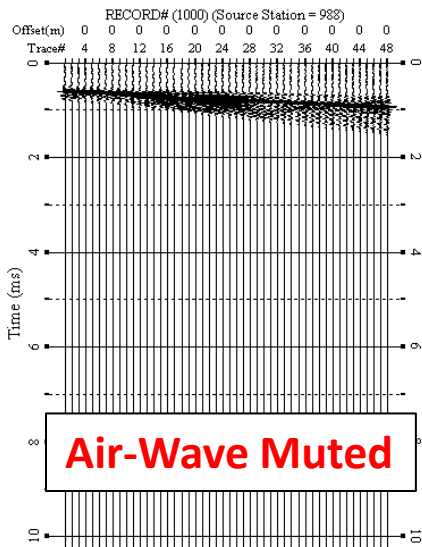
$d=0.269$ m @ 3476 Hz**



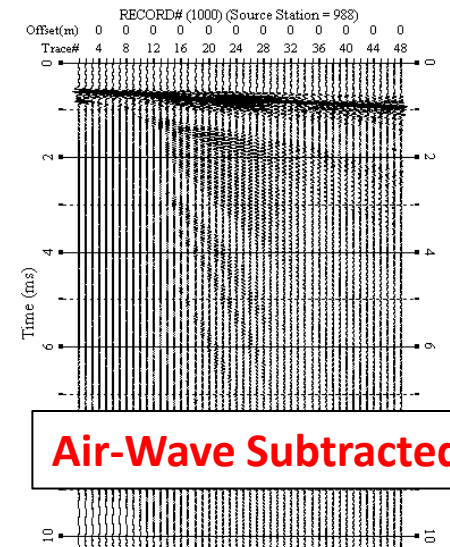
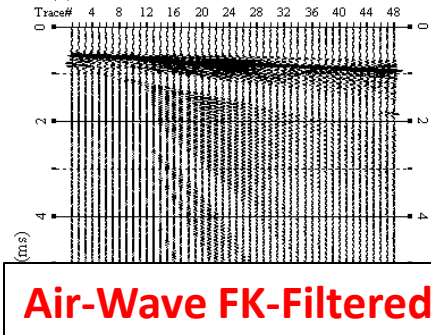
$d=0.098$ m @ 9636 Hz**



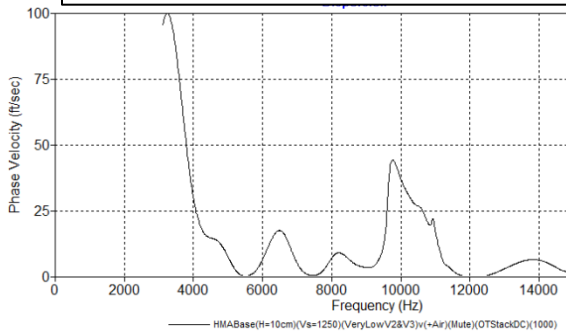
IE* – Different Process to Attenuate Air Wave



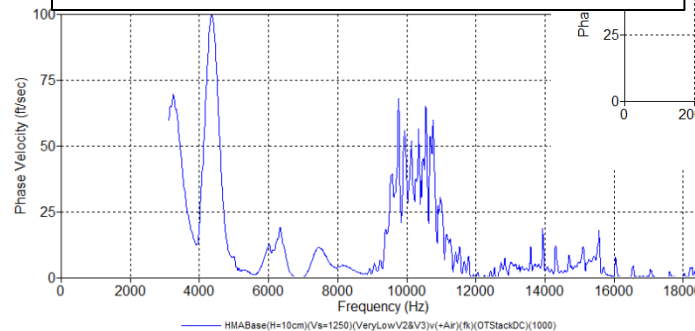
- * *Bjurstrom and Ryden (2016)*
- ** *Observed peak frequency (fr) and calculated thickness (d)*
- + *Air wave subtracted by using the moving-window LMO stack.*



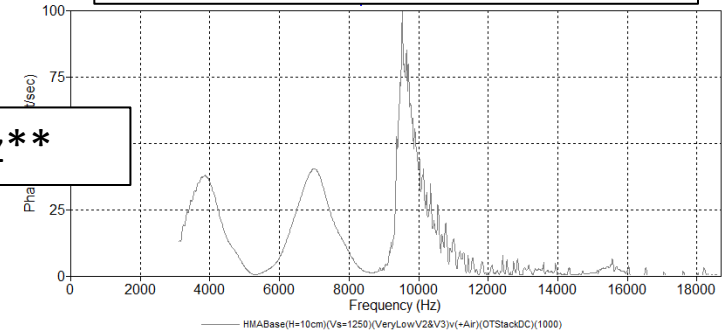
$d=0.288 \text{ m @ } 3246 \text{ Hz}^{**}$



$d=0.215 \text{ m @ } 4356 \text{ Hz}^{**}$



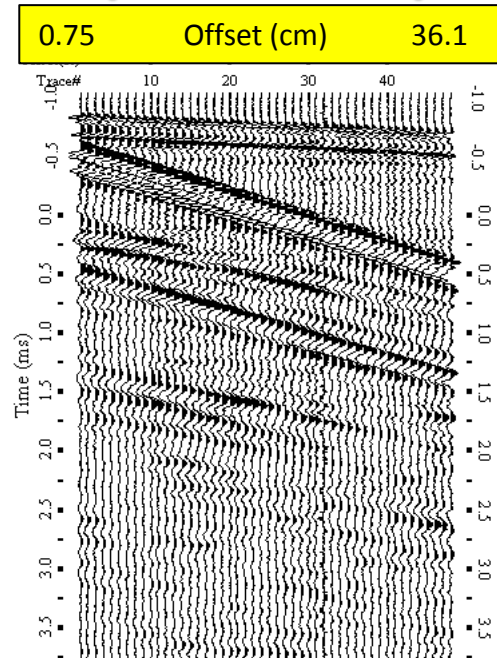
$d=0.098 \text{ m @ } 9636 \text{ Hz}^{**}$



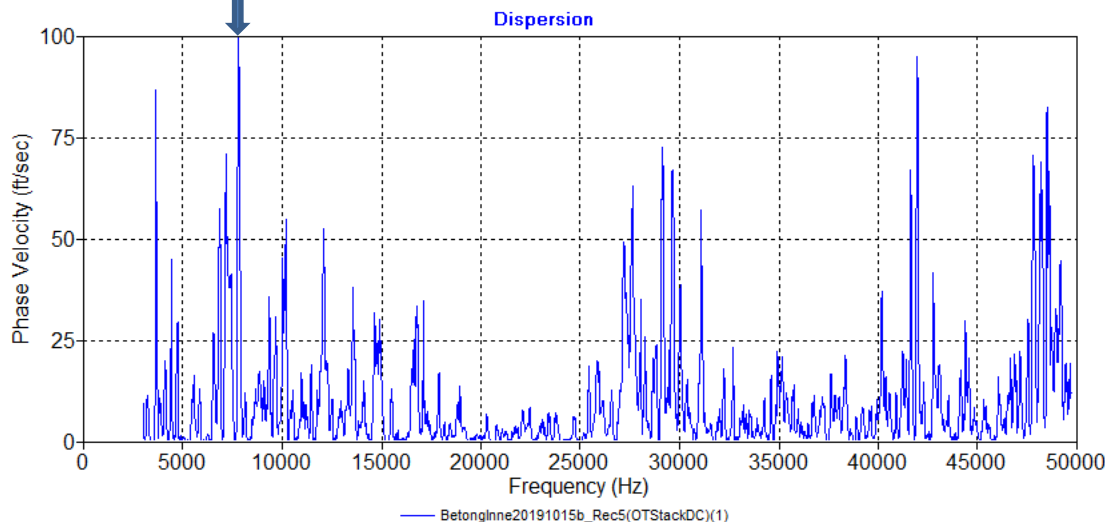
IE* – Non-Contact (Microphone) Measurement**



Full 48-Channel Record
($dx^+ = 0.75$ cm)

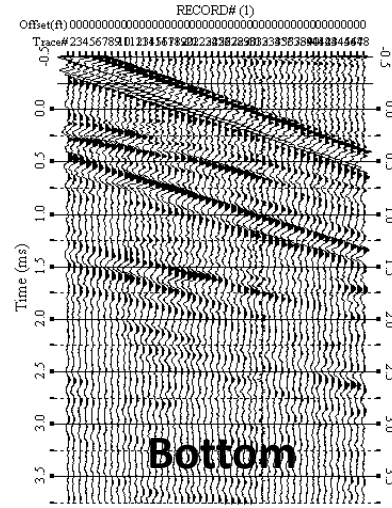
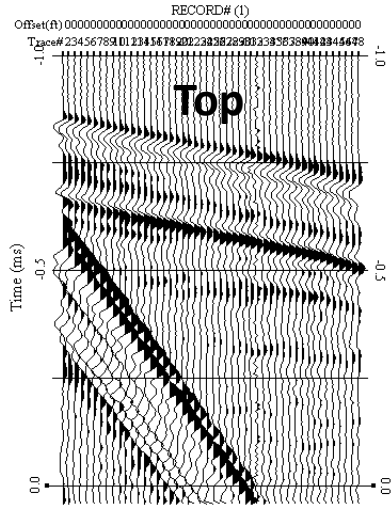
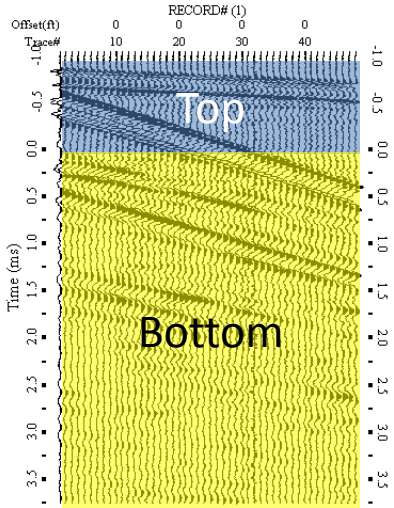


$d=0.261$ m @ 7801 Hz***

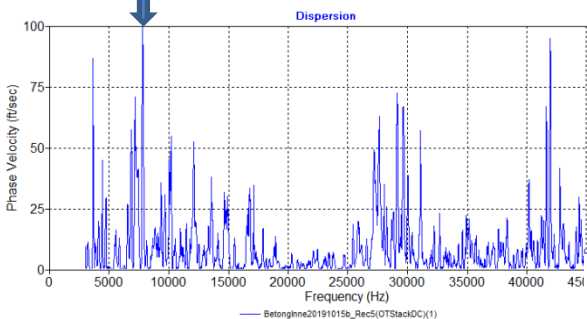


- * *Bjurstrom and Ryden (2016)*
- ** *Indoor concrete pavement (Lund University, Sweden); thickness (d) = 0.26 m, $V_s = 2600$ m/s, and $POS = 0.20$ (from Ryden et al., 2006).*
- *** *Observed peak frequency (f_r) and calculated thickness (d)*
- + *Channel (i.e., MEMS microphone) spacing*

IE* – Different Part of the Record

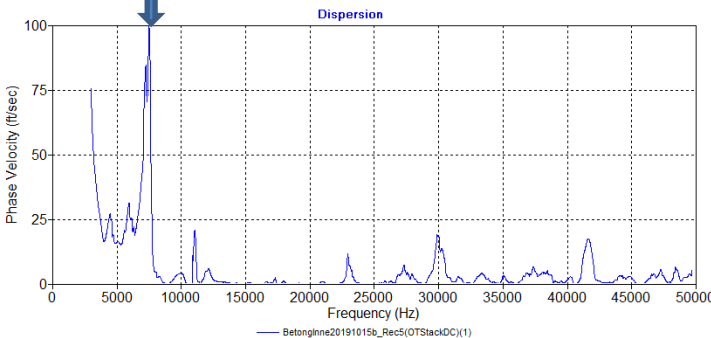


d=0.261 m @ 7801 Hz**

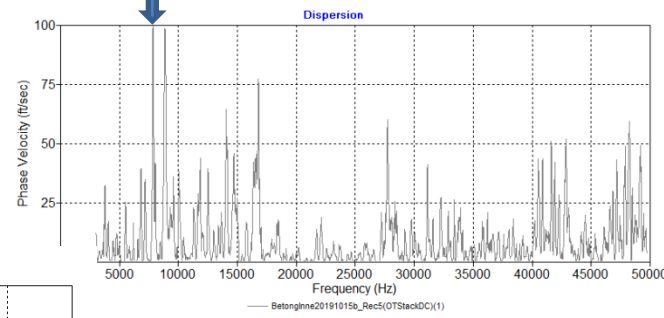


* *Bjurstrom and Ryden (2016)*
** *Observed peak frequency (fr) and calculated thickness (d)*

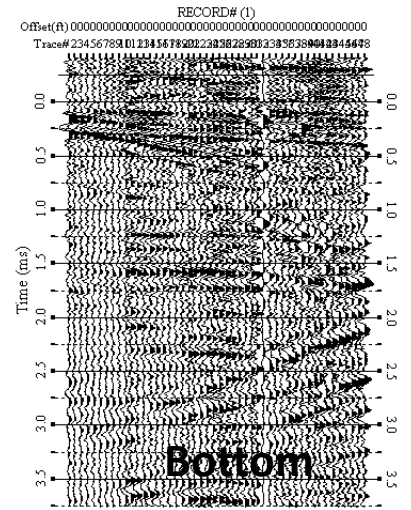
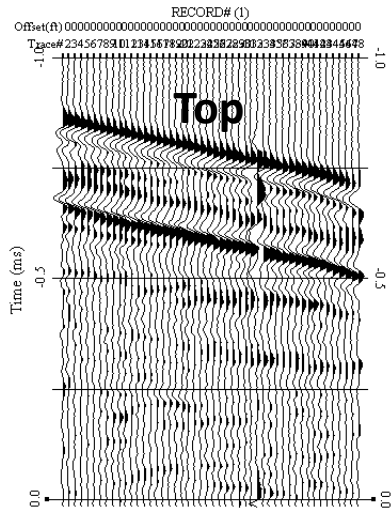
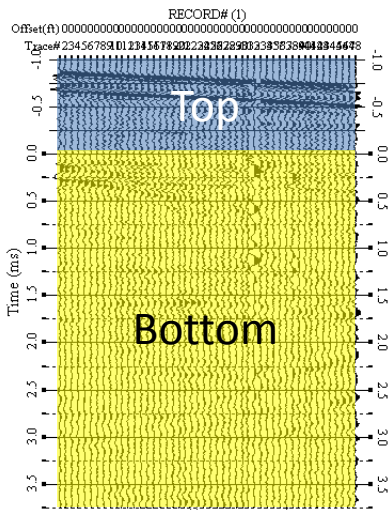
d=0.272 m @ 7481 Hz**



d=0.260 m @ 7842 Hz**



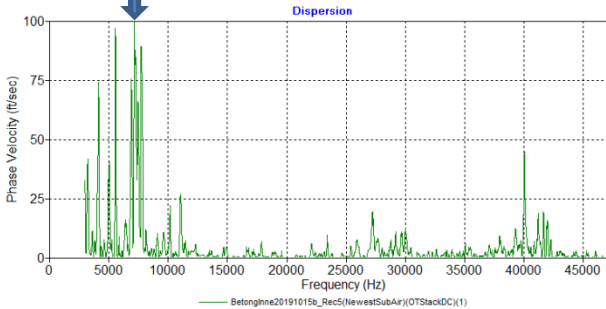
IE* – Different Part of Air Subtracted



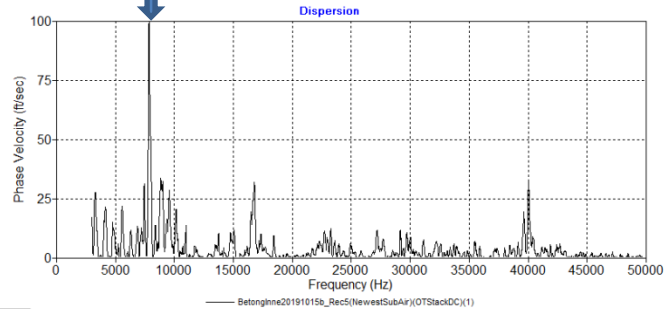
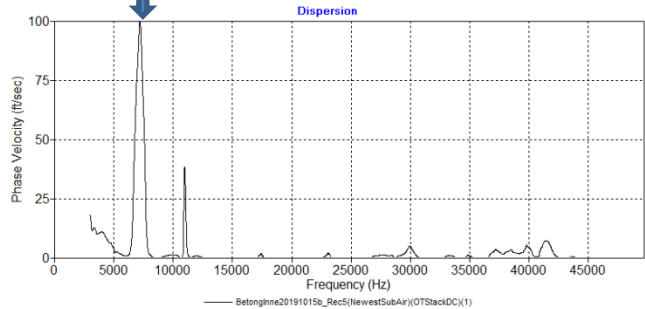
$d=0.284 \text{ m @ } 7171 \text{ Hz}^{**}$

* *Bjurstrom and Ryden (2016)*
 ** *Observed peak frequency (fr) and calculated thickness (d)*

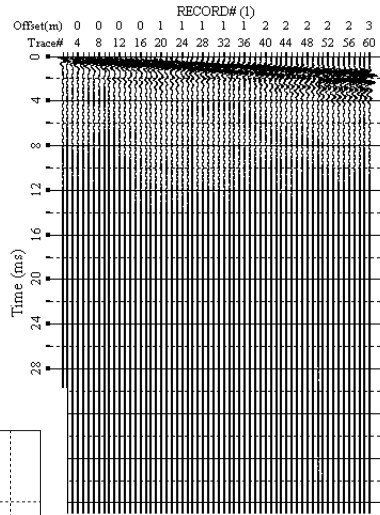
$d=0.260 \text{ m @ } 7841 \text{ Hz}^{**}$



$d=0.283 \text{ m @ } 7211 \text{ Hz}^{**}$

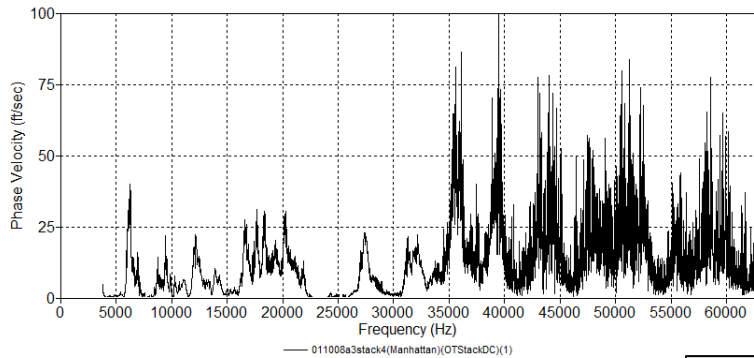


Real Data I-70 (Concrete Pavement)

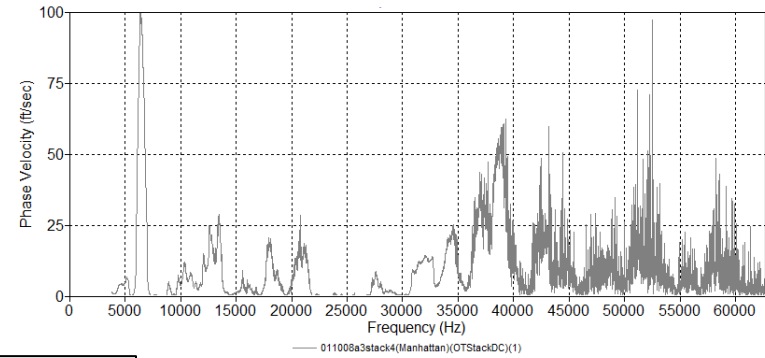


$V_s=2400$, $POS=0.20$, $V_p=3919$
[From Lamb (A0) Analysis]
 $d=0.3$ m (on site measurement)

Full Record (1-60 trc)
 $d=0.048$ m @ 39462 Hz*

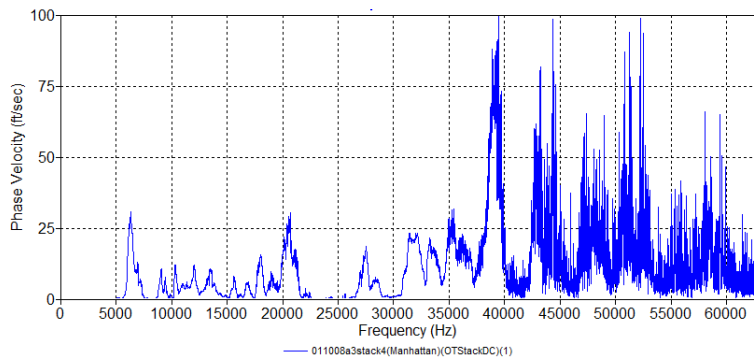


Partial Record (1-10 trc)
 $d=0.293$ m @ 6422 Hz*

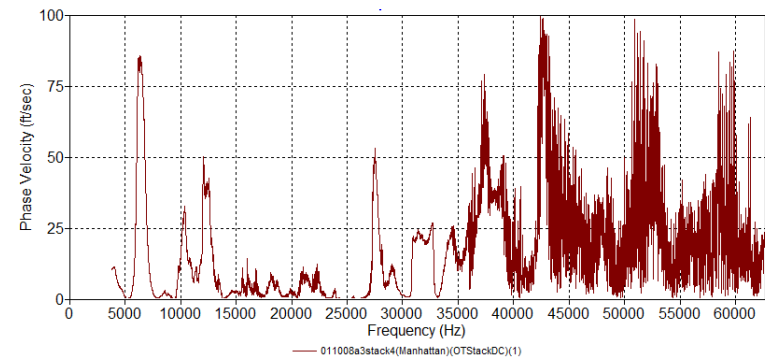


* *Observed peak frequency (fr) and calculated thickness (d)*

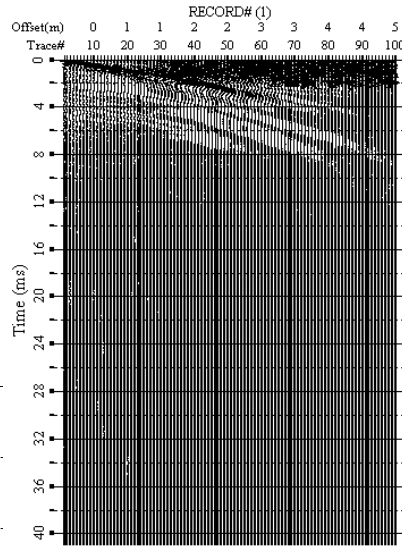
Partial Record (1-30 trc)
 $d=0.048$ m @ 39462 Hz*



Partial Record (1-6 trc)
 $d=0.044$ m @ 42452 Hz*

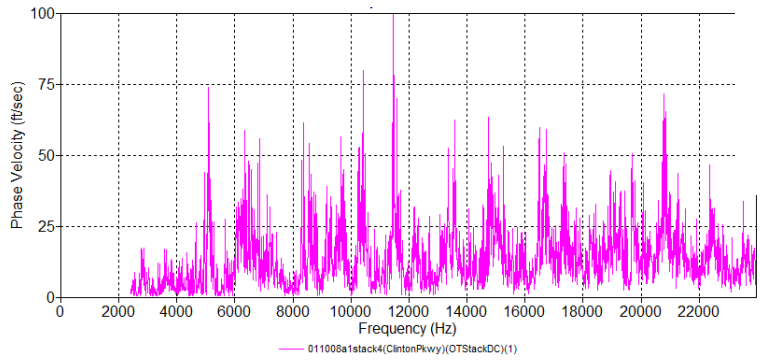


Real Data (Asphalt Pavement)

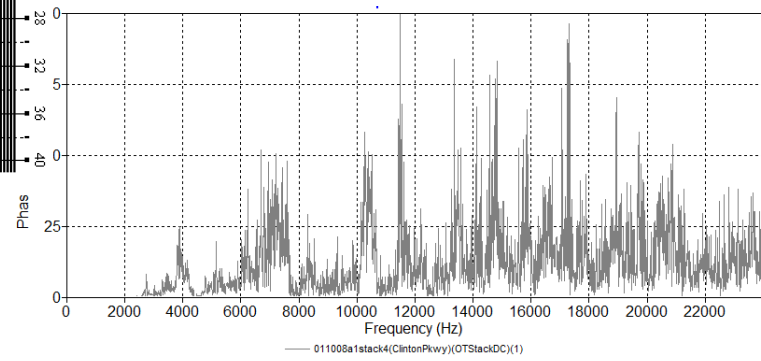


Used for IE Analysis (from A0 analysis):
 $V_s=1250$, $POS=0.333$, $V_p=2498$

Full Record (1-100 trc)
 $d=0.105$ m @ 11468 Hz*

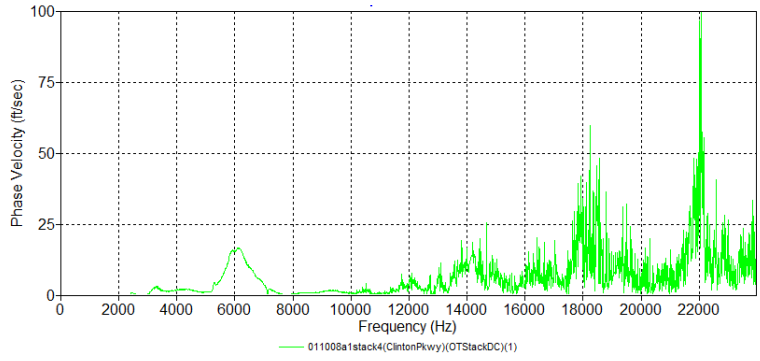


Partial Record (1-50 trc)
 $d=0.104$ m @ 11488 Hz*

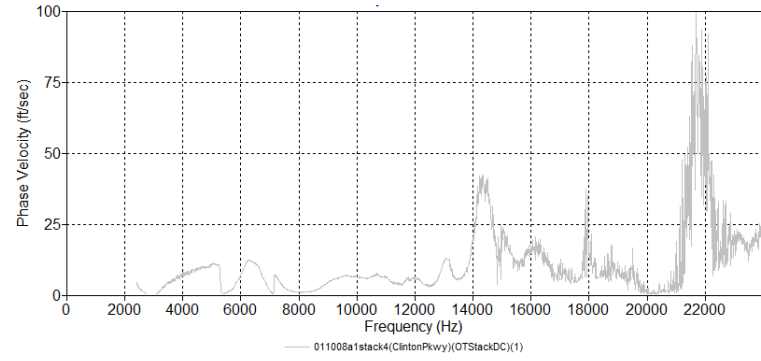


* *Observed peak frequency (fr)*
and calculated thickness (d)

Partial Record (1-12 trc)
 $d=0.054$ m @ 22068 Hz*

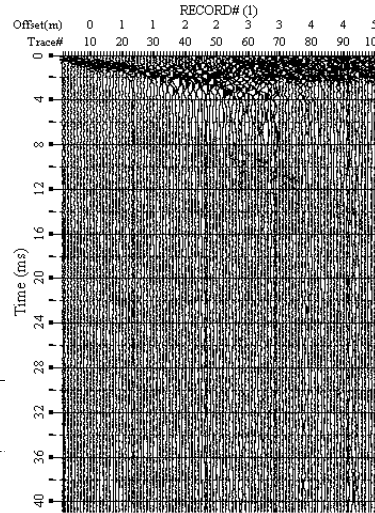
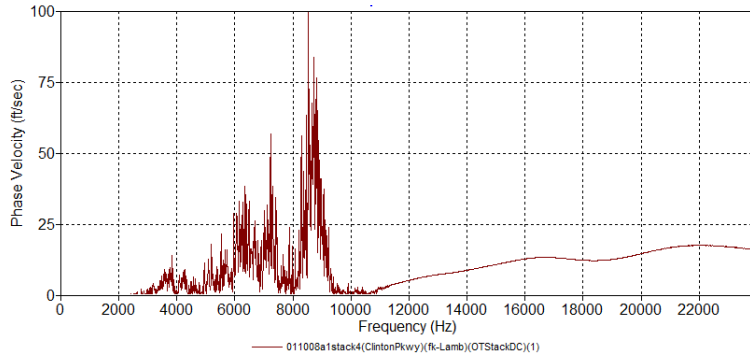


Partial Record (1-6 trc)
 $d=0.055$ m @ 21698 Hz*



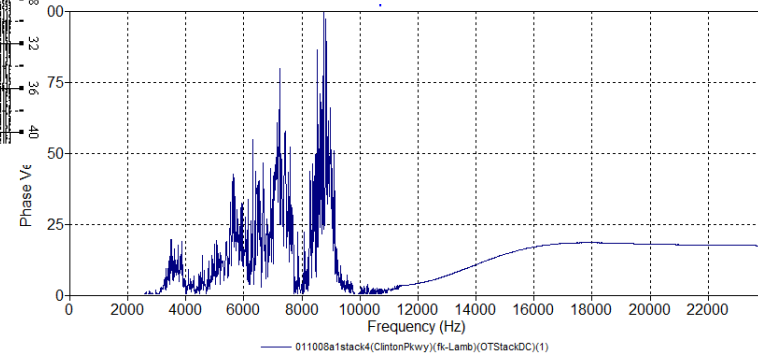
Real Data (Asphalt Pavement) ("Lamb FK'd")

Full Record (1-100 trc)
d=0.140 m @ 8538 Hz*



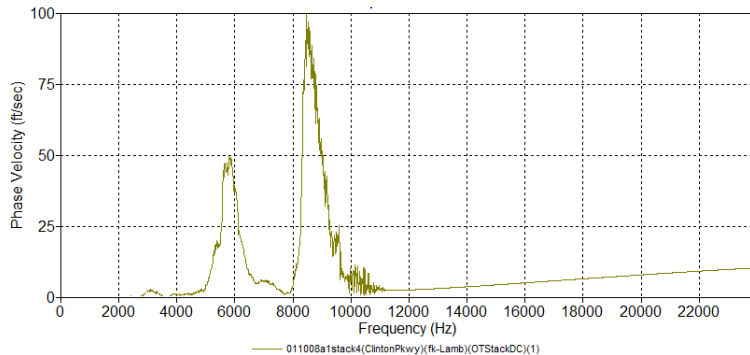
Used for IE Analysis (from A0 analysis):
Vs=1250, POS=0.333, Vp=2498

Partial Record (1-50 trc)
d=0.137 m @ 8748 Hz*



* *Observed peak frequency (fr)
and calculated thickness (d)*

Partial Record (1-12 trc)
d=0.141 m @ 8478 Hz*



Partial Record (1-6 trc)
d=0.142 m @ 8418 Hz*

