Part 4

Future Study

1. Higher Modes

Advantages of Calculating Shear-wave Velocity from Surface Waves with Higher Modes

Why Use Higher Modes?

Outline

- Introduction
- Modeling Results
- A Real-World Example
- Discussion and Conclusions

Introduction

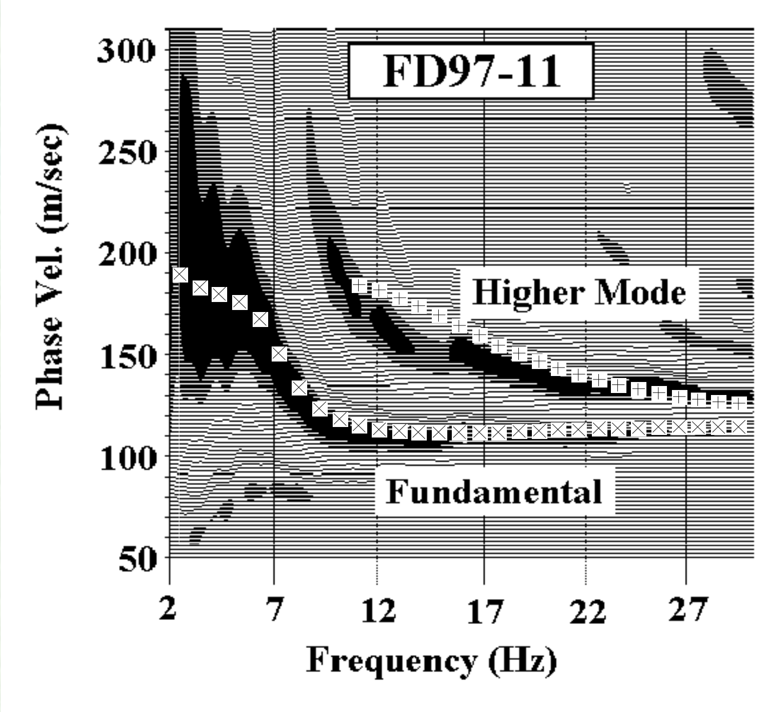
What are higher modes?

More than one phase velocity can be associated with a given frequency of Rayleigh wave simply because these waves can travel at different velocities for a given frequency.

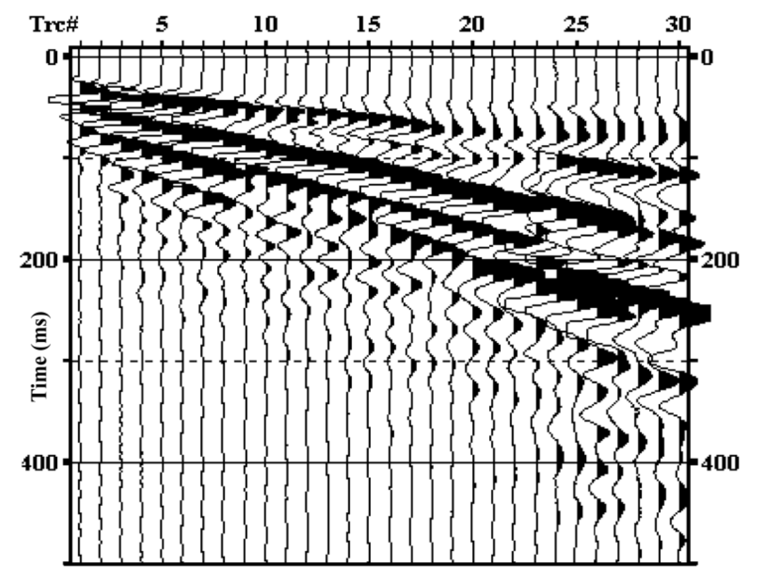
The lowest velocity for any given frequency is called the ***fundamental-mode*** velocity (or the first mode). The next higher velocity above the fundamental-mode phase velocity is called the ***second-mode*** velocity, and so on.

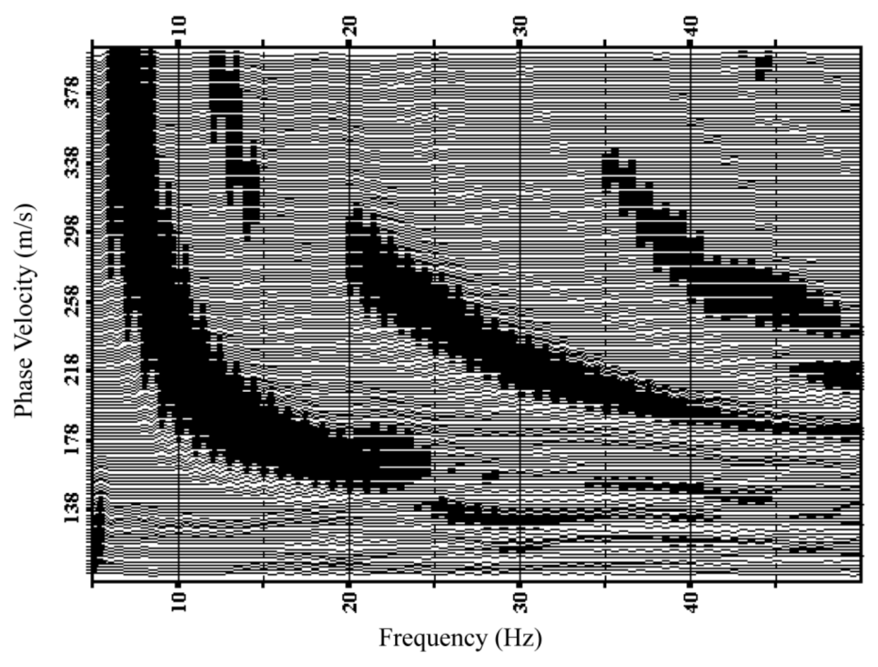
Why do we need higher modes?

In some situations, higher modes take more energy than the fundamental mode in a higher frequency range, which means the fundamental-mode data may not be available in the higher frequency range and higher modes are the only choice.



An Example of Higher Modes



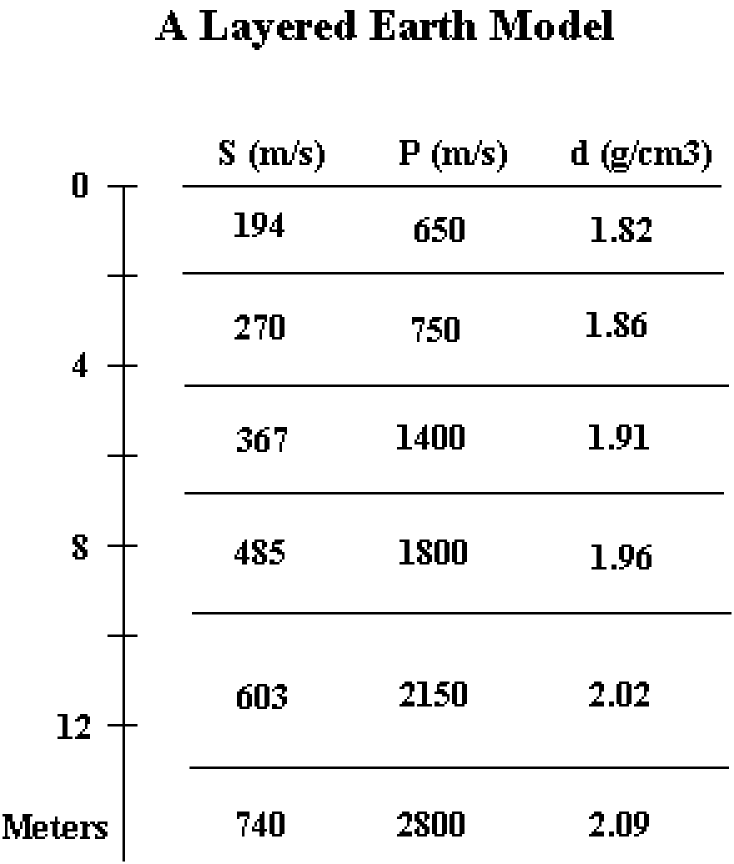


Data acquired in San Jose, California, in 1998

Modeling Results

The six layer model is used to analyze

1. the sensitivity of higher modes of surface waves,
2. investigation depth,
3. stability during inversion.



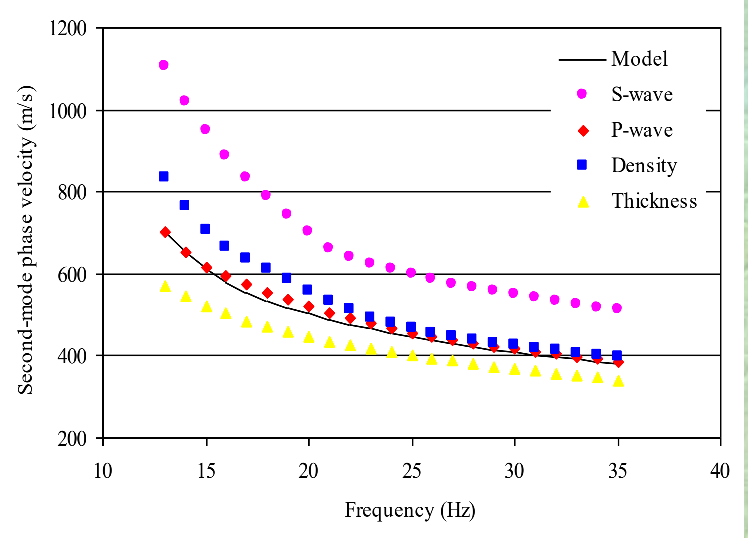
A Layered Earth Model

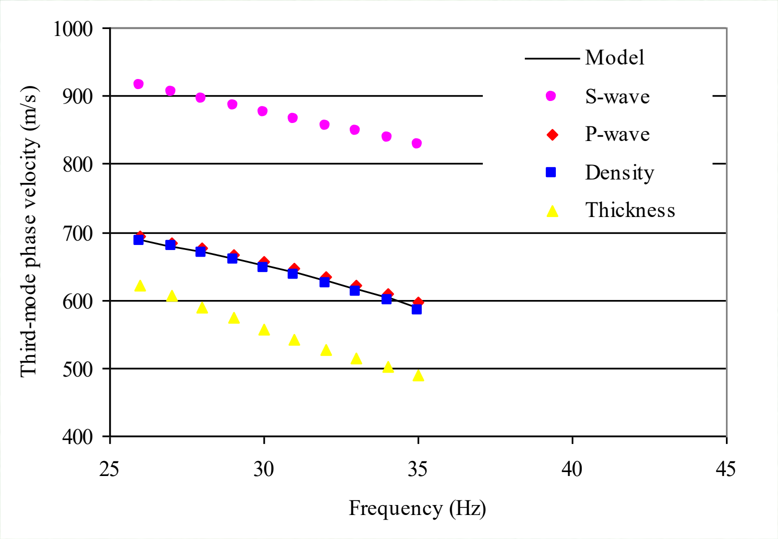
S (m/s)	P (m/s)	d (g/cm3)
194	650	1.82
270	750	1.86
367	1400	1.91
485	1800	1.96
603	2150	2.02
740	2800	2.09

Sensitivity of Higher Modes

Second mode

Third mode





Contribution to the higher-mode Rayleigh-wave phase velocity by a 25% change in each earth parameter.

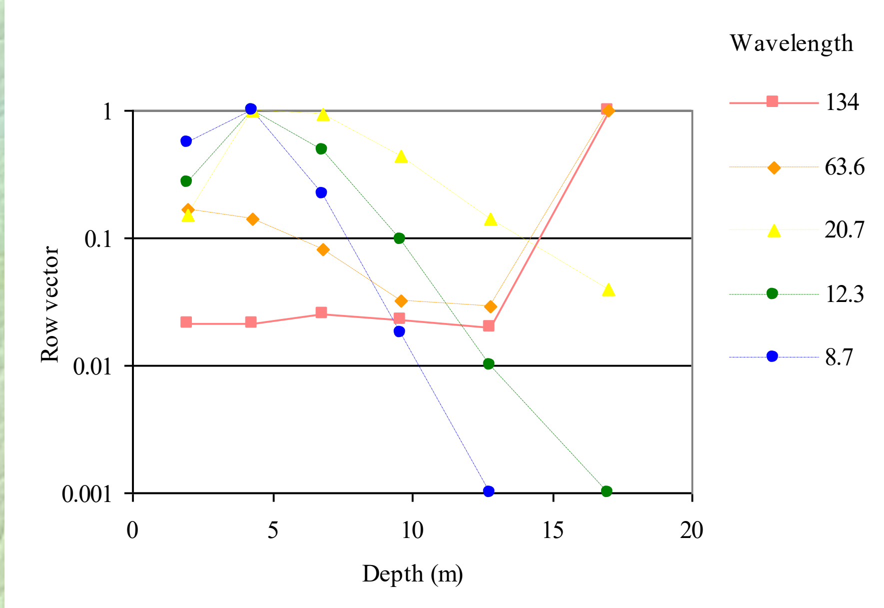
Penetrating Depth of Higher Modes

- Experimental analysis indicates that energy of higher modes tends to become more dominant as the source distance increases.
- The Jacobian matrix of the higher-mode Rayleigh-wave data suggests higher-mode data have deeper investigation depths than do the fundamental-mode data.

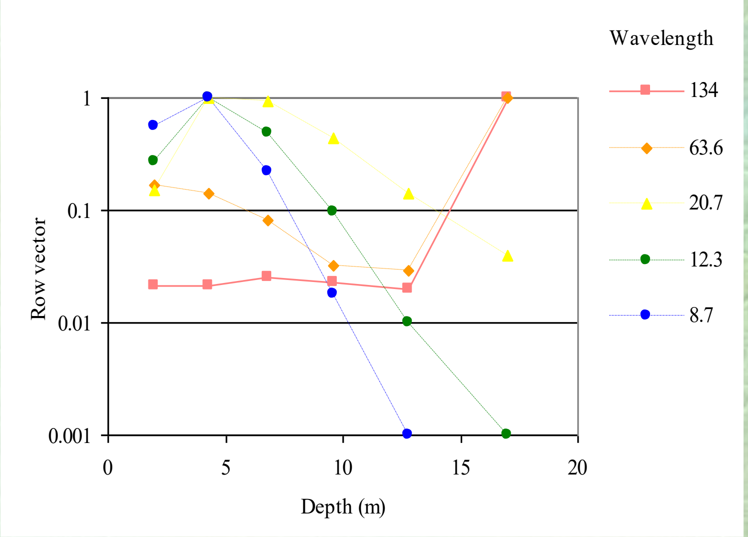
Penetrating Depth

The open circles are the row vectors of the Jacobian matrix associated with the shortest wavelength data.

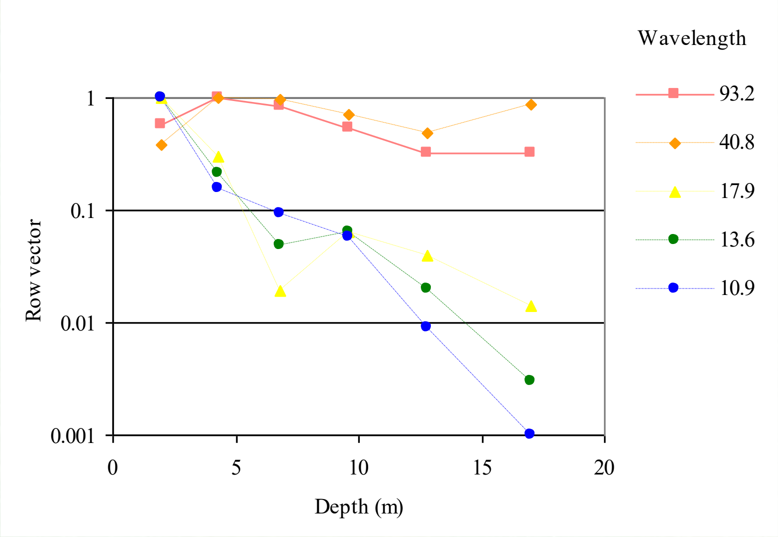
A wavelength of 8.7 m reaches zero at a depth of 13 m for the fundamental-mode data



Penetrating Depth Comparison

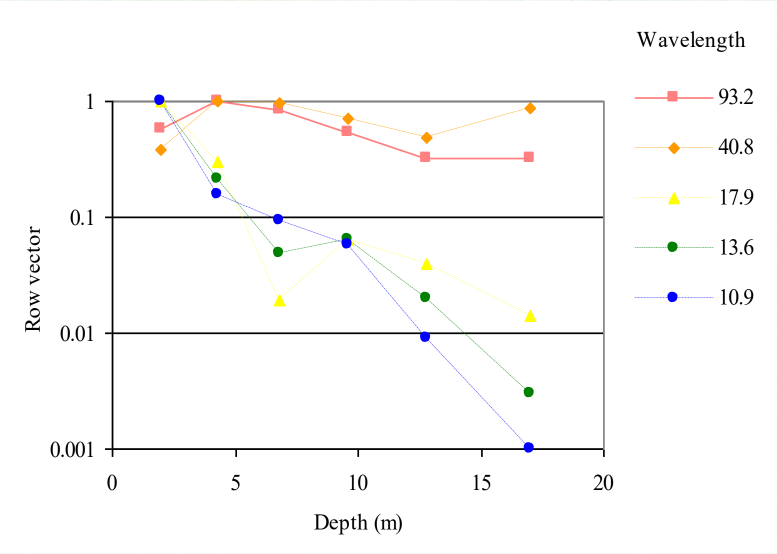


Fundamental mode

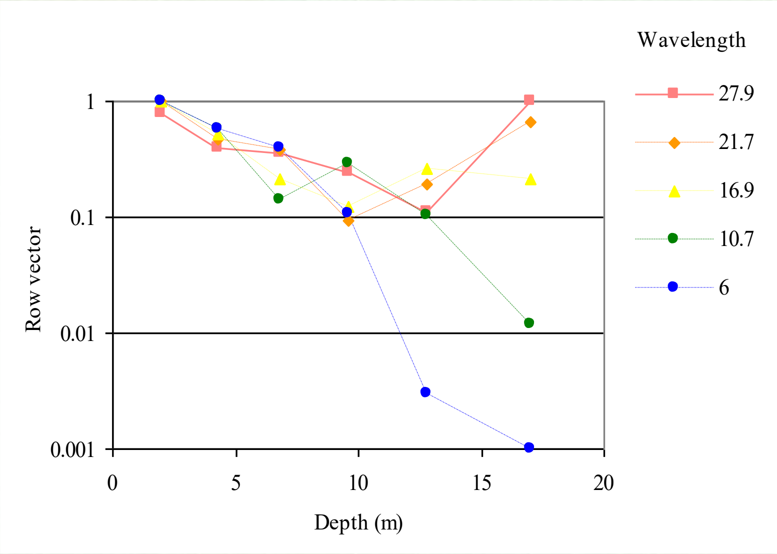


Second mode

Penetrating Depth Comparison



Second mode



Third mode

Conclusion on Penetrating Depth

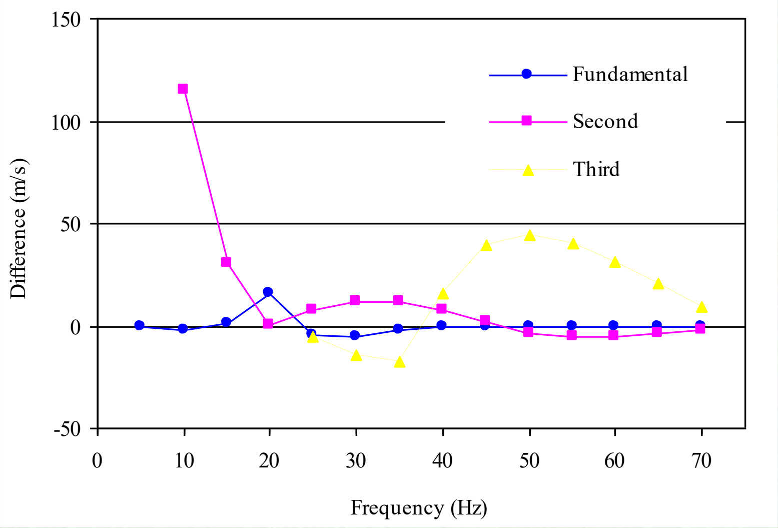
- Higher-mode Rayleigh-wave data can "see" deeper when compared to the same wavelength components of the fundamental-mode Rayleigh-wave data.

Stability of Inversion with Higher Modes

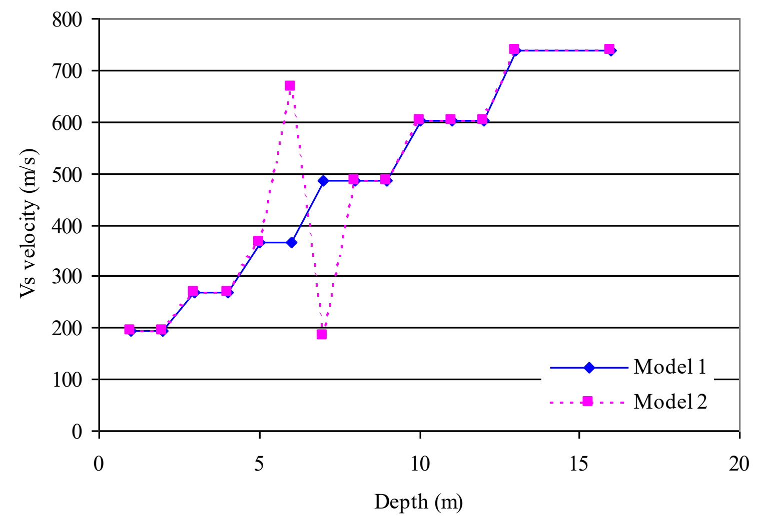
- The most significant result is that higher-mode data stabilizes the inversion process and increases the resolution of inverted S-wave velocities.

Stability of Inversion

Differences in phase velocity



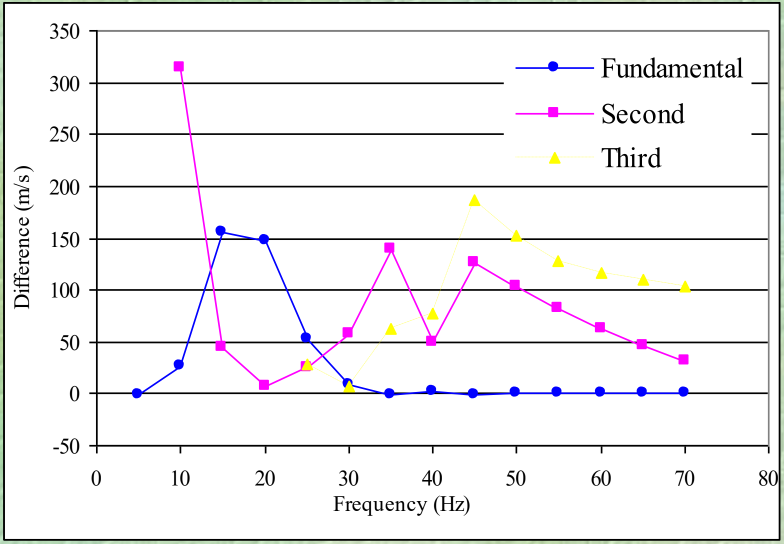
S-wave velocity models



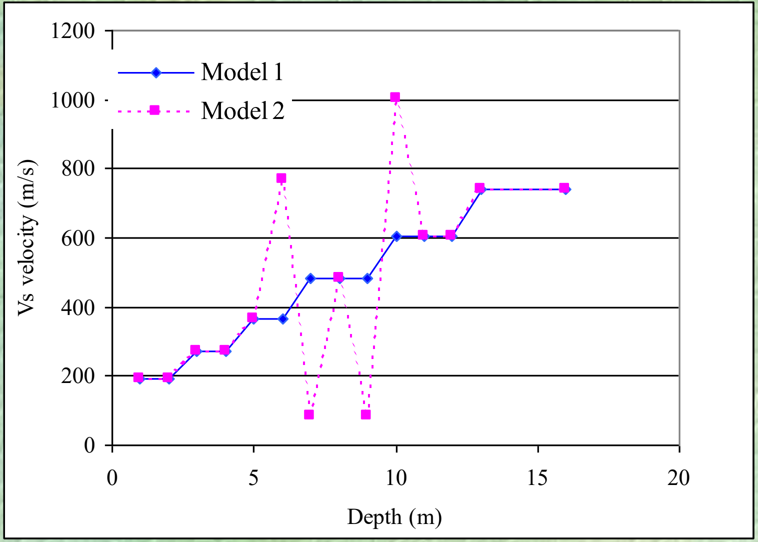
A difference of more than 100% in S-wave velocity models at depths of 6 m and 7 m only result in a standard deviation of
4.6 m/s in the fundamental-mode data,
33.5 m/s in second-mode data, and
27.3 m/s in the third-mode data.

Stability of Inversion

Differences in phase velocity



S-wave velocity models



A 100% difference in S-wave velocity models at depths of 6 m and 7 m and 9 m and 10 m only result in a standard deviation of

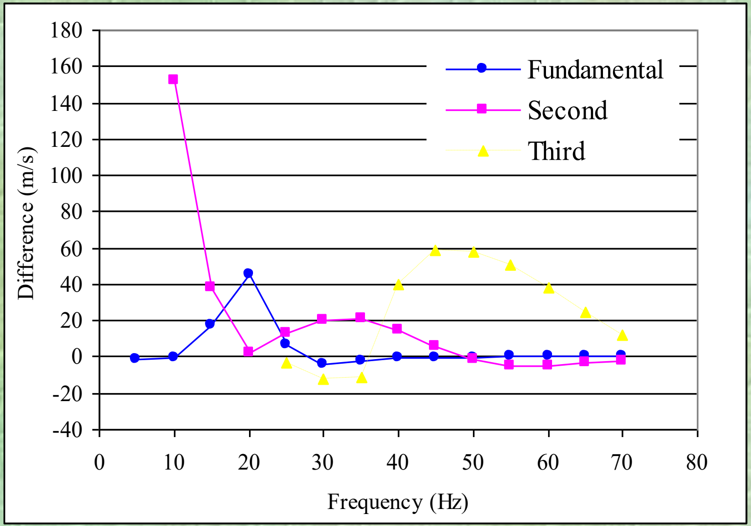
59 m/s in the fundamental-mode data,

113 m/s in second-mode data, and

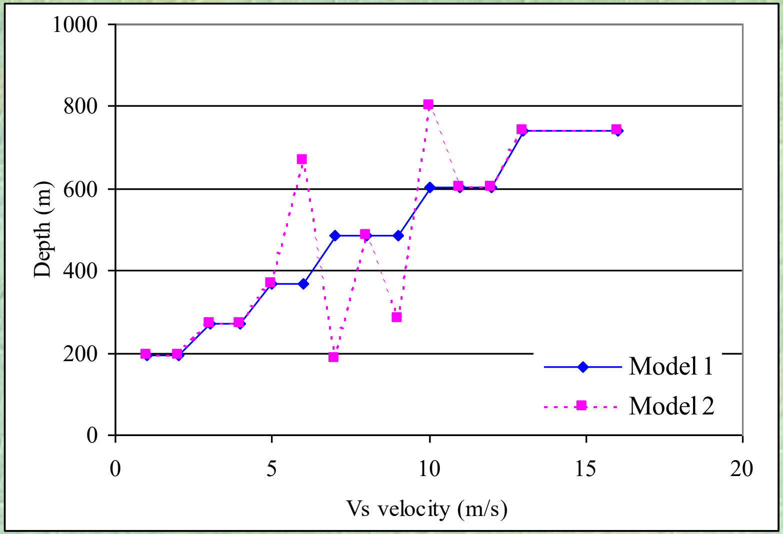
110 m/s in the third-mode data.

Stability of Inversion

Differences in phase velocity



S-wave velocity models



A 80% difference in S-wave velocity models at depths of 6 m and 7 m and 9 m and 10 m only result in a standard deviation of

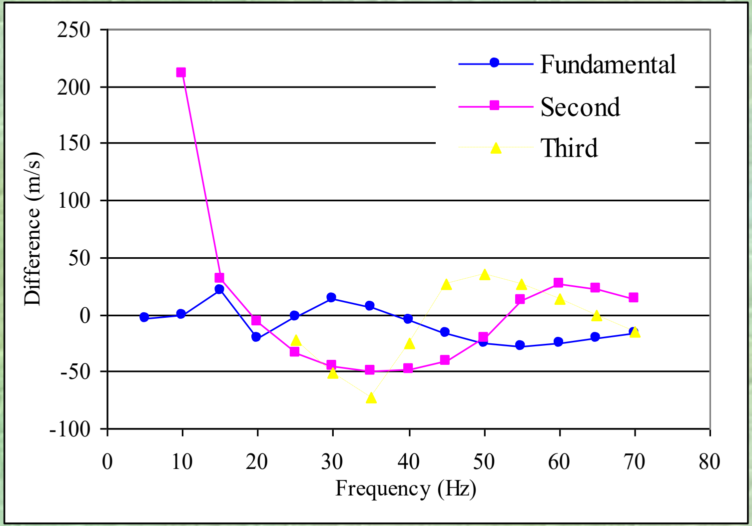
13 m/s in the fundamental-mode data,

45 m/s in second-mode data, and

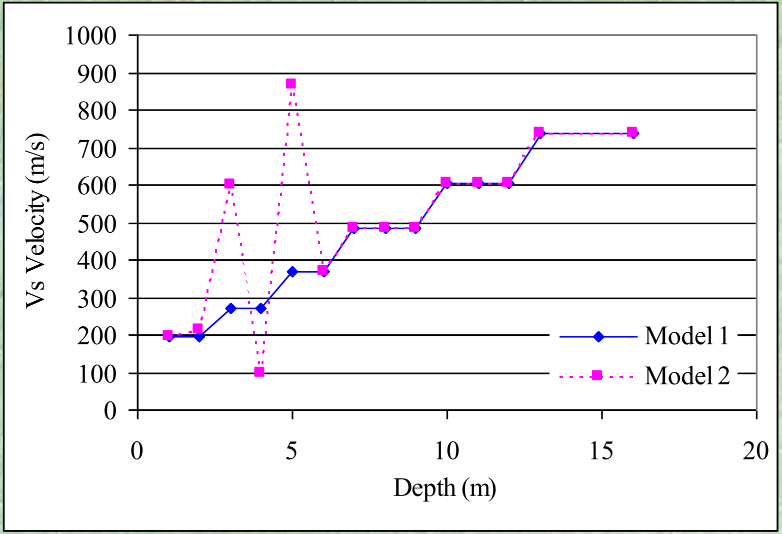
37 m/s in the third-mode data.

Stability of Inversion

Differences in phase velocity



S-wave velocity models



80% difference in S-wave velocity models at depths from 3 m to 6 m only result in a standard deviation of

17 m/s in the fundamental-mode data

66 m/s in second-mode data

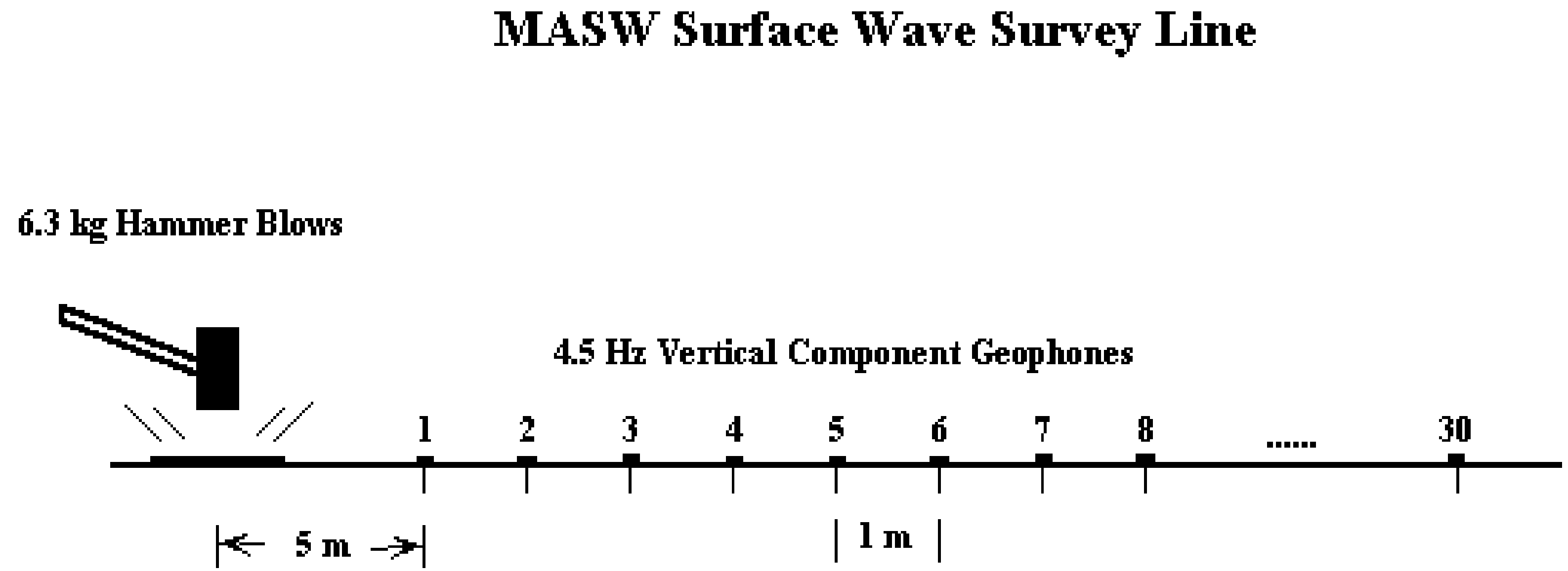
35 m/s in the third-mode data.

Conclusion on Stability

- An inversion with higher mode data can reject “irrational” model 2 due to its higher RMS error. Model 2 may be accepted by an inversion only with the fundamental mode data due to its lower RMS error.
- A stabilized inversion can be achieved by including higher mode data in an inversion process.

A Real-world Example
San Jose, California, Fall of 1998

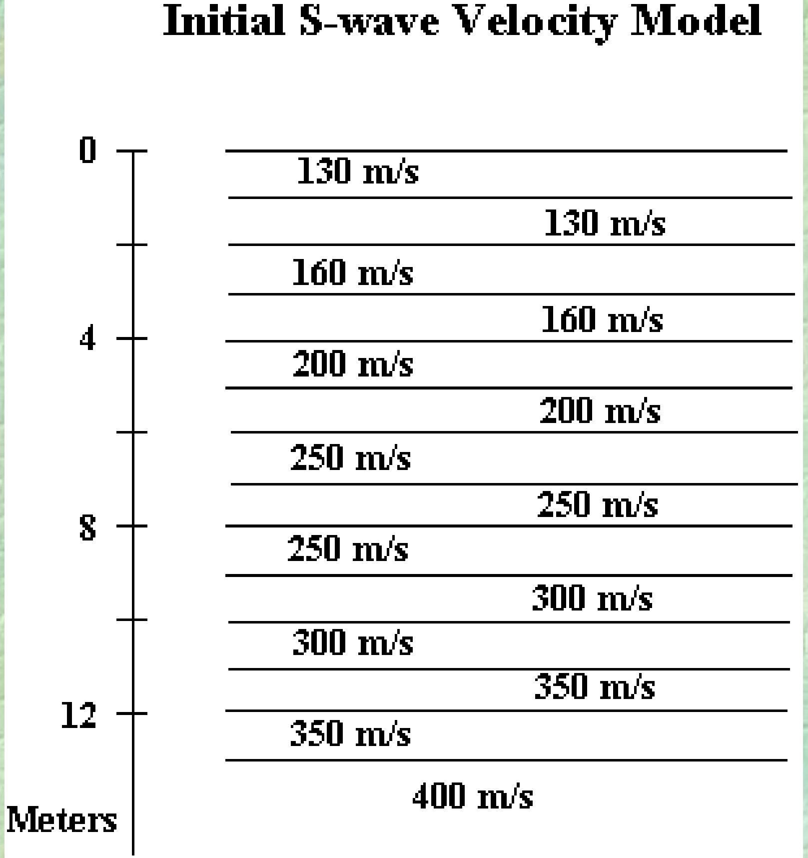
Field Layout



To determine S-wave velocity in near-surface materials up to 10 m deep.

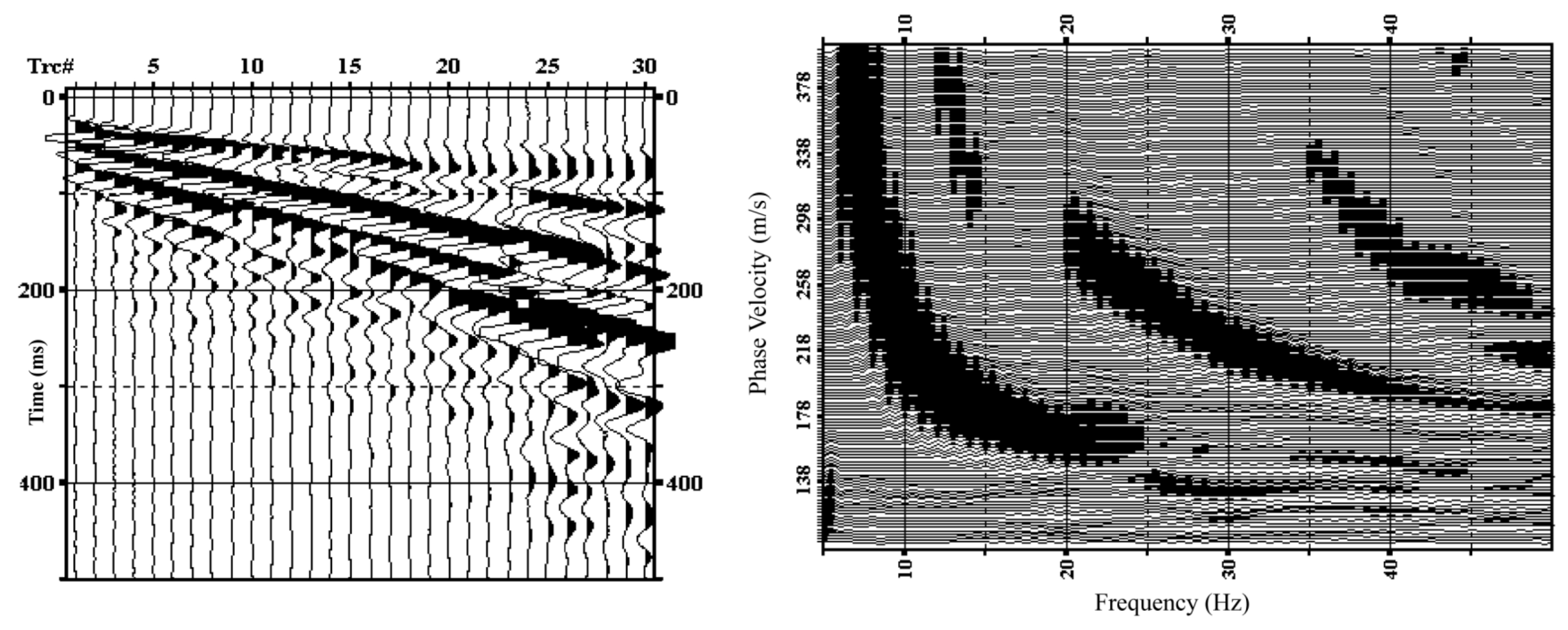
Layered Model

- A fourteen-layer model with each layer 1 m in thickness.



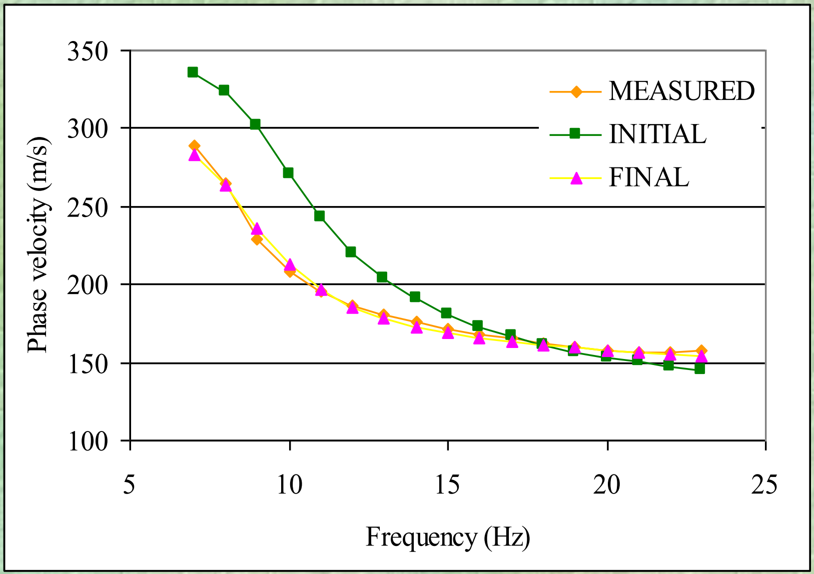
Initial S-wave Velocity Model

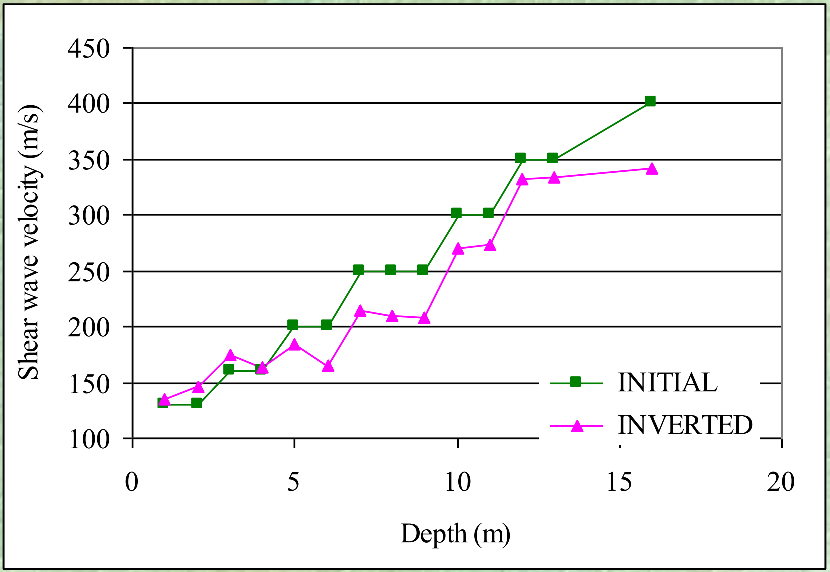
Shot gather and its image in F-K domain



Fundamental Mode Data

(Set One)

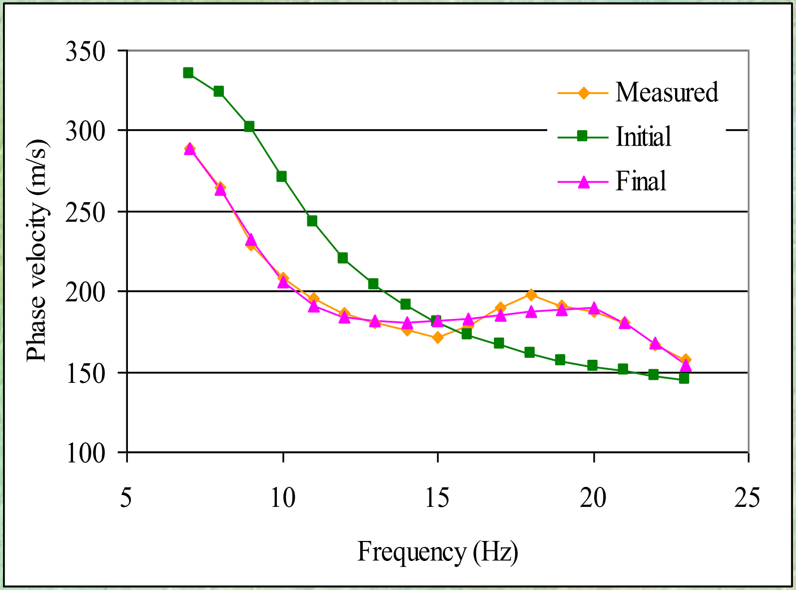


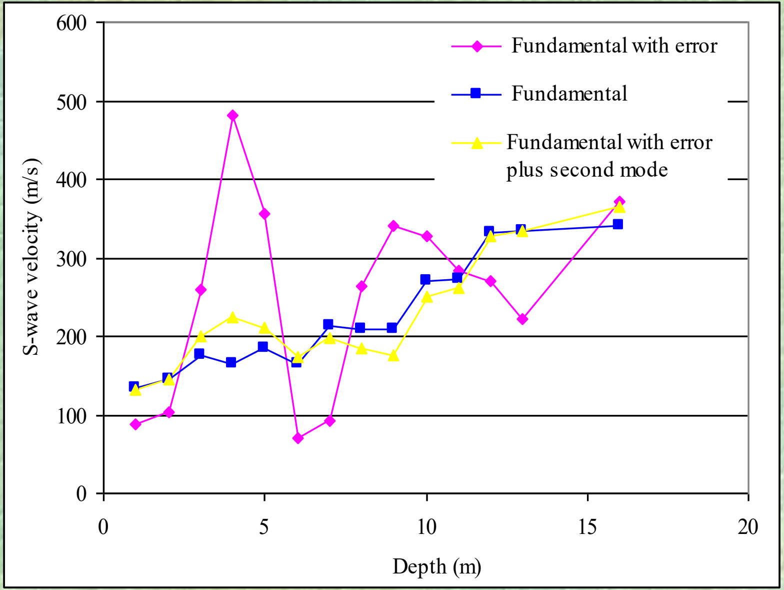


Pink lines present results of inversion of fundamental mode of surface wave data with errors.

Fundamental Mode Data with Errors

(Set Two)

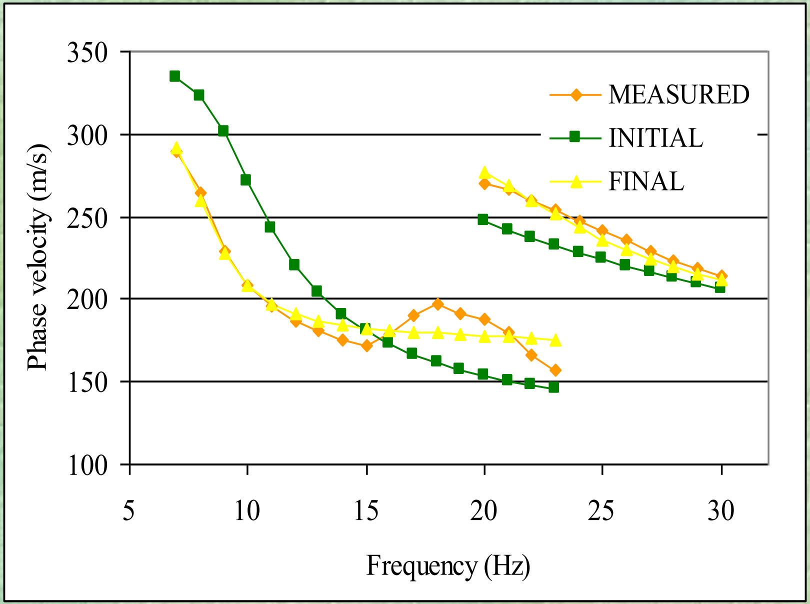


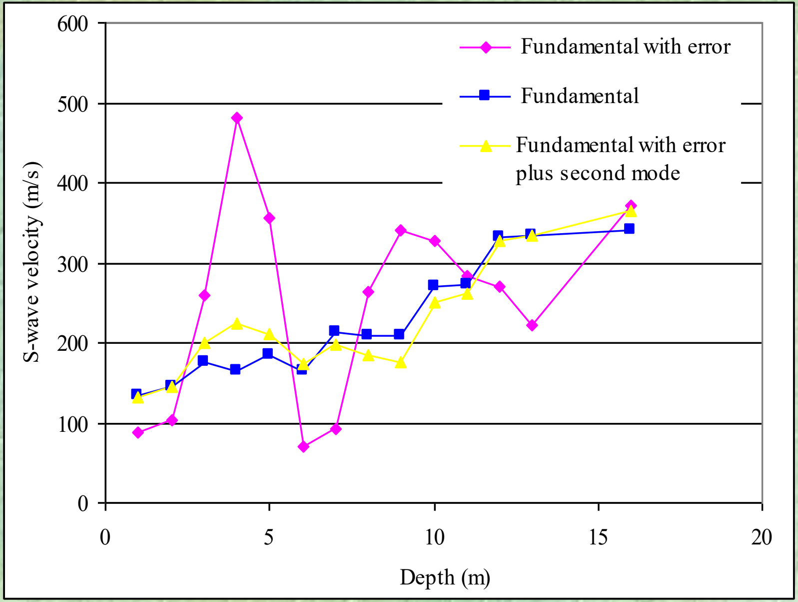


Pink lines present results of inversion of fundamental mode of surface wave data with errors.

Fundamental Mode Data with Errors Plus the Second Mode Data

(Set Three)



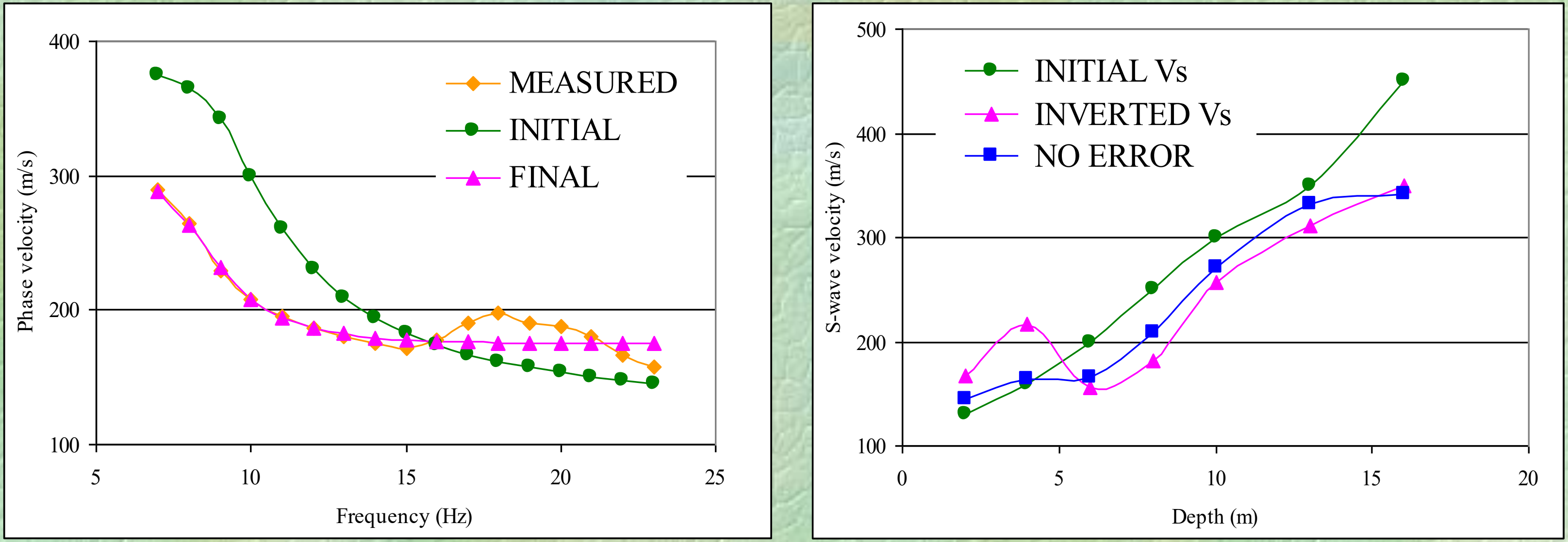


Yellow lines present results of inversion of fundamental mode of surface wave data with errors plus the second mode data.

Discussion

- In the real world, we normally make a choice between error and resolution of a model. The instability that we see in the inverted S-wave velocities of data set two is error in the inverted model, which can be reduced by reducing the resolution of the model.

Trade off Between Resolution and Error



Resolution is reduced by one half (layer thickness is increased to 2 m) to obtain a stable result (less model errors).

Acknowledgments

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Future Study (continuation)

2. Accuracy of phase velocity

To extract phase velocity from higher resolution image in the f-k domain and/or in the wavelet domain.

3. Group Velocity and Attenuation

To extract S-wave velocity from group velocity and/or attenuation curve.

Both group velocity and attenuation are related to derivatives of phase velocity.

4. Wave equation modeling and laboratory modeling

To model cases such as a dipping layered earth model, voids in layered earth models, layered model with S-wave velocity inversion (higher velocity on the top of lower velocity layer).

To verify if there are any surface wave reflections and/or refractions. If yes, in what situations they will occur.

5. Resolution

Horizontal resolution of inverted S-wave velocity changes with depth due difference wavelengths.

Vertical resolution—study by modeling?

6. Surface Wave Tomography

New 3-D near-surface technology