Acoustic laboratory measurements of hydrate-bearing Bentheim sandstones

Mathias M. Sæther[1], Per Lunde[1,3], Stian Almenningen[2], Geir Ersland[2]

1. Acoustics Group, Department of Physics and Technology, University of Bergen
2. Petroleum and process technology group, Department of Physics and Technology, University of Bergen
3. NORCE, Bergen

Outline

- Motivation
- Experimental setup and measurement method
  - Pressure cell
  - Solid buffer method
  - Fourier spectrum and first arrival of pulse signal processing techniques
- Methane hydrate measurements and modelling
  - Numerical models
  - Elastic wave velocities
- Conclusions and further work

Motivation

- Methane hydrates:
  - Vast quantities in subsea reservoirs
  - Harvest energy
  - Acoustic methods (Moridis et al. 2009)

https://www.japantimes.co.jp/news/2012/03/13/reference/methane-hydrate-energy-solution/#.XD3dhVxKhaQ

https://www.japantimes.co.jp/news/2012/03/13/reference/methane-hydrate-energy-solution/#.XD3dhVxKhaQ

[1] G. J. Moridis et al., “Toward production from gas hydrates”, SPE Reservoir Evaluation and Engineering 12(5), pp. 745–771 (2009).

Acoustic parameters and hydrate bearing sediments

- Acoustic parameters (c_P, c_S) depending on [2,3]

[2] W. F. Waite, W. J. Winters, and D. H. Mason, “Methane hydrate formation in partially water-saturated ottawa sand”, American Mineralogist 89(8-9), pp. 1202–1207 (2004).
[3] J. A. Priest, A. I. Best, and C. R. Clayton, “A laboratory investigation into the seismic velocities of methane gas hydrate-bearing sand", Journal of Geophysical Research: Solid Earth 110(B4), pp. B04102 (2005).
[4] A. E. Peksa, K. H. A. Wolf, and P. L. Zitha, “Bentheimer sandstone revisited for experimental purposes”, Marine and Petroleum Geology 67, pp. 701–719 (2015).

Acoustic parameters and hydrate bearing sediments

- Acoustic parameters (c_P, c_S) depending on [2,3]
  - Hydrate saturation: $$S_H = \frac{\text{Volume hydrate}}{\text{pore volume}}$$
  - Water saturation: $$S_w = \frac{\text{Volume water}}{\text{pore volume}}$$
  - Free gas saturation: $$S_g = \frac{\text{Volume free gas}}{\text{pore volume}}$$
  - Initial water saturation: $$S_{w0} = \frac{\text{Init. volume water}}{\text{pore volume}}$$
  - Sediment composition [4]
  - Measurement frequency [3]
  - Hydrate growth pattern

[2] W. F. Waite, W. J. Winters, and D. H. Mason, “Methane hydrate formation in partially water-saturated ottawa sand”, American Mineralogist 89(8-9), pp. 1202–1207 (2004).
[3] J. A. Priest, A. I. Best, and C. R. Clayton, “A laboratory investigation into the seismic velocities of methane gas hydrate-bearing sand", Journal of Geophysical Research: Solid Earth 110(B4), pp. B04102 (2005).
[4] A. E. Peksa, K. H. A. Wolf, and P. L. Zitha, “Bentheimer sandstone revisited for experimental purposes”, Marine and Petroleum Geology 67, pp. 701–719 (2015).

Acoustic parameters and hydrate bearing sediments

- Acoustic parameters (c_P, c_S) depending on [2,3]
  - Hydrate saturation: $$S_H = \frac{\text{Volume hydrate}}{\text{pore volume}}$$
  - Water saturation: $$S_w = \frac{\text{Volume water}}{\text{pore volume}}$$
  - Free gas saturation: $$S_g = \frac{\text{Volume free gas}}{\text{pore volume}}$$
  - Initial water saturation: $$S_{w0} = \frac{\text{Init. volume water}}{\text{pore volume}}$$
  - Sediment composition [4]
  - Measurement frequency [3]
  - Hydrate growth pattern

[2] W. F. Waite, W. J. Winters, and D. H. Mason, “Methane hydrate formation in partially water-saturated ottawa sand”, American Mineralogist 89(8-9), pp. 1202–1207 (2004).
[3] J. A. Priest, A. I. Best, and C. R. Clayton, “A laboratory investigation into the seismic velocities of methane gas hydrate-bearing sand", Journal of Geophysical Research: Solid Earth 110(B4), pp. B04102 (2005).
[4] A. E. Peksa, K. H. A. Wolf, and P. L. Zitha, “Bentheimer sandstone revisited for experimental purposes”, Marine and Petroleum Geology 67, pp. 701–719 (2015).

Acoustic parameters and hydrate bearing sediments

- Acoustic parameters (c_P, c_S) depending on [2,3]
  - Hydrate saturation: $$S_H = \frac{\text{Volume hydrate}}{\text{pore volume}}$$
  - Water saturation: $$S_w = \frac{\text{Volume water}}{\text{pore volume}}$$
  - Free gas saturation: $$S_g = \frac{\text{Volume free gas}}{\text{pore volume}}$$
  - Initial water saturation: $$S_{w0} = \frac{\text{Init. volume water}}{\text{pore volume}}$$
  - Sediment composition [4]
  - Measurement frequency [3]
  - Hydrate growth pattern

[2] W. F. Waite, W. J. Winters, and D. H. Mason, "Methane hydrate formation in partially water-saturated ottawa sand", American Mineralogist 89(8-9), pp. 1202–1207 (2004).
[3] J. A. Priest, A. I. Best, and C. R. Clayton, "A laboratory investigation into the seismic velocities of methane gas hydrate-bearing sand", Journal of Geophysical Research: Solid Earth 110(B4), pp. B04102 (2005).
[4] A. E. Peksa, K. H. A. Wolf, and P. L. Zitha, "Bentheimer sandstone revisited for experimental purposes", Marine and Petroleum Geology 67, pp. 701–719 (2015).

Acoustic parameters and hydrate bearing sediments

- Acoustic parameters (c_P, c_S) depending on [2,3]
  - Hydrate saturation: $S_H = \dfrac{\text{Volume hydrate}}{\text{pore volume}}$
  - Water saturation: $S_w = \dfrac{\text{Volume water}}{\text{pore volume}}$
  - Free gas saturation: $S_g = \dfrac{\text{Volume free gas}}{\text{pore volume}}$
  - Initial water saturation: $S_{w0} = \dfrac{\text{Init. volume water}}{\text{pore volume}}$
  - Sediment composition [4]
  - Measurement frequency [3]
  - Hydrate growth pattern

[2] W. F. Waite, W. J. Winters, and D. H. Mason, “Methane hydrate formation in partially water-saturated ottawa sand”, American Mineralogist 89(8-9), pp. 1202–1207 (2004).
[3] J. A. Priest, A. I. Best, and C. R. Clayton, “A laboratory investigation into the seismic velocities of methane gas hydrate-bearing sand", Journal of Geophysical Research: Solid Earth 110(B4), pp. B04102 (2005).
[4] A. E. Peksa, K. H. A. Wolf, and P. L. Zitha, “Bentheimer sandstone revisited for experimental purposes”, Marine and Petroleum Geology 67, pp. 701–719 (2015).

Acoustic parameters and hydrate bearing sediments

- Acoustic parameters (c_P, c_S) depending on [2,3]
  - Hydrate saturation: $S_H = \frac{\text{Volume hydrate}}{\text{pore volume}}$
  - Water saturation: $S_w = \frac{\text{Volume water}}{\text{pore volume}}$
  - Free gas saturation: $S_g = \frac{\text{Volume free gas}}{\text{pore volume}}$
  - Initial water saturation: $S_{w0} = \frac{\text{Init. volume water}}{\text{pore volume}}$
  - Sediment composition [4]
  - Measurement frequency [3]
  - Hydrate growth pattern

[2] W. F. Waite, W. J. Winters, and D. H. Mason, “Methane hydrate formation in partially water-saturated ottawa sand”, American Mineralogist 89(8-9), pp. 1202–1207 (2004).
[3] J. A. Priest, A. I. Best, and C. R. Clayton, “A laboratory investigation into the seismic velocities of methane gas hydrate-bearing sand", Journal of Geophysical Research: Solid Earth 110(B4), pp. B04102 (2005).
[4] A. E. Peksa, K. H. A. Wolf, and P. L. Zitha, “Bentheimer sandstone revisited for experimental purposes”, Marine and Petroleum Geology 67, pp. 701–719 (2015).

Acoustic parameters and hydrate bearing sediments

- Acoustic parameters (c_P, c_S) depending on [2,3]
  - Hydrate saturation: $$S_H = \frac{\text{Volume hydrate}}{\text{pore volume}}$$
  - Water saturation: $$S_w = \frac{\text{Volume water}}{\text{pore volume}}$$
  - Free gas saturation: $$S_g = \frac{\text{Volume free gas}}{\text{pore volume}}$$
  - Initial water saturation: $$S_{w0} = \frac{\text{Init. volume water}}{\text{pore volume}}$$
  - Sediment composition [4]
  - Measurement frequency [3]
  - Hydrate growth pattern

[2] W. F. Waite, W. J. Winters, and D. H. Mason, “Methane hydrate formation in partially water-saturated ottawa sand”, American Mineralogist 89(8-9), pp. 1202–1207 (2004).
[3] J. A. Priest, A. I. Best, and C. R. Clayton, “A laboratory investigation into the seismic velocities of methane gas hydrate-bearing sand", Journal of Geophysical Research: Solid Earth 110(B4), pp. B04102 (2005).
[4] A. E. Peksa, K. H. A. Wolf, and P. L. Zitha, “Bentheimer sandstone revisited for experimental purposes”, Marine and Petroleum Geology 67, pp. 701–719 (2015).

Acoustic parameters and hydrate bearing sediments

- Acoustic parameters (c_P, c_S) depending on [2,3]
  - Hydrate saturation: $$S_H = \frac{\text{Volume hydrate}}{\text{pore volume}}$$
  - Water saturation: $$S_w = \frac{\text{Volume water}}{\text{pore volume}}$$
  - Free gas saturation: $$S_g = \frac{\text{Volume free gas}}{\text{pore volume}}$$
  - Initial water saturation: $$S_{w0} = \frac{\text{Init. volume water}}{\text{pore volume}}$$
  - Sediment composition [4]
  - Measurement frequency [3]
  - Hydrate growth pattern ←

[2] W. F. Waite, W. J. Winters, and D. H. Mason, "Methane hydrate formation in partially water-saturated ottawa sand", American Mineralogist 89(8-9), pp. 1202–1207 (2004).
[3] J. A. Priest, A. I. Best, and C. R. Clayton, "A laboratory investigation into the seismic velocities of methane gas hydrate-bearing sand", Journal of Geophysical Research: Solid Earth 110(B4), pp. B04102 (2005).
[4] A. E. Peksa, K. H. A. Wolf, and P. L. Zitha, "Bentheimer sandstone revisited for experimental purposes", Marine and Petroleum Geology 67, pp. 701–719 (2015).

Prior research and objectives

- Prior research:
  - Sonic frequencies (typically < 20-30 kHz): Resonance methods [3,5]
  - Ultrasonic frequencies (typically > 100 kHz): First arrival of the pulse [2,6,7]

- Objectives:
  - Fourier spectrum method (350 kHz - 600 kHz) during hydrate growth
  - Compare Fourier spectrum and first arrival of the pulse signal processing methods [8].
  - Control S_H, S_w, S_g, S_{w0},
  - Implement numerical models and discuss measurements (hydrate growth pattern)

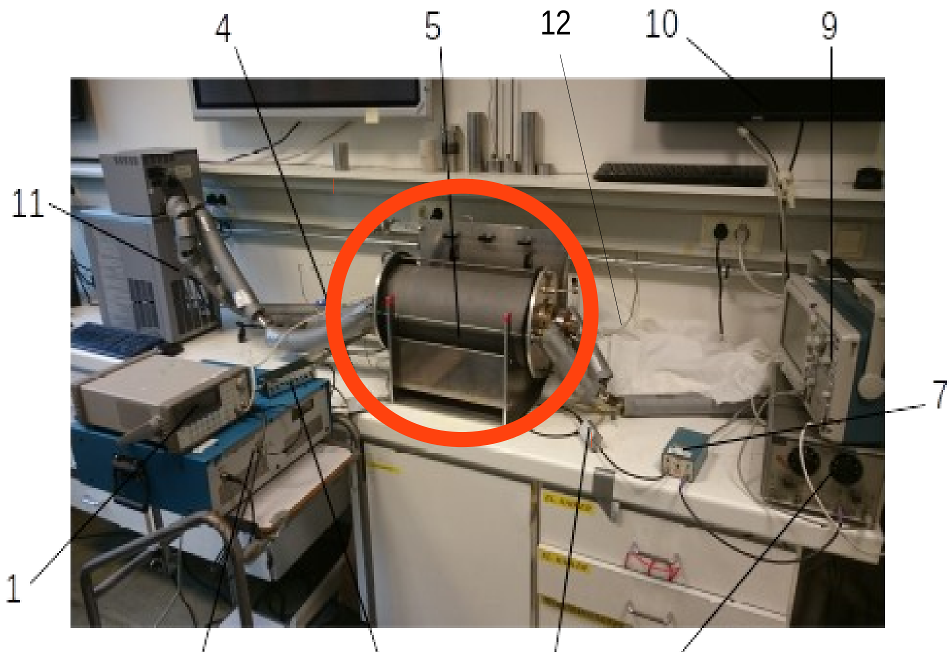
[5] S. Nakagawa et al., “Split Hopkinson Resonant Bar test and its application for seismic property characterization of geological media", in Proceedings of the 44th US Rock Mechanics Symposium, American Rock Mechanics Association, Salt Lake City, Utah, (2010).
[6] W. J. Winters, I. A. Pecher, W. F. Waite, and D. H. Mason, “Physical properties and rock physics models of sediment containing natural and laboratory-formed methane gas hydrate", American Mineralogist 89(8-9), pp. 1221-1227 (2004).
[7] Q. Zhang, F. G. Li, C. Y. Sun, Q. P. Li, X. Y. Wu, B. Liu, and G. J. Chen, “Compressional wave velocity measurements through sandy sediments containing methane hydrate", American Mineralogist 96(10), pp. 1425-1432 (2011).
[8] J. B. Molyneux and D. R. Schmitt, "First-break timing: Arrival onset times by direct correlation," Geophysics 64, pp. 1492-1501 (1999).

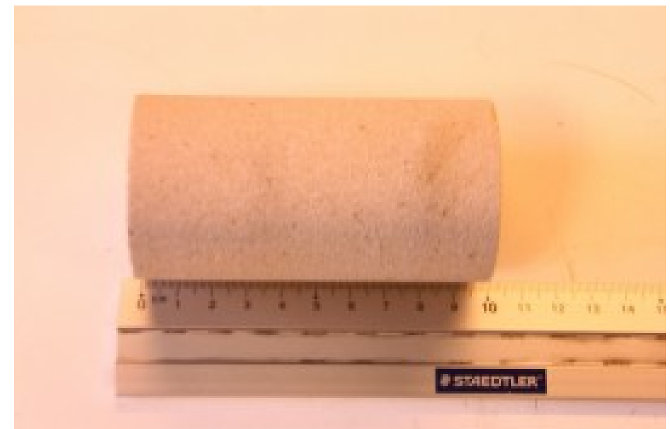
Outline

- Motivation
- Experimental setup and measurement method
  - Pressure cell
  - Solid buffer method
  - Fourier spectrum and first arrival of pulse signal processing techniques
- Methane hydrate measurements and modelling
  - Numerical models
  - Elastic wave velocities
- Conclusions and further work

Experimental setup

- Methane hydrate formation condition in pressure cell: 83 bar and 4°C





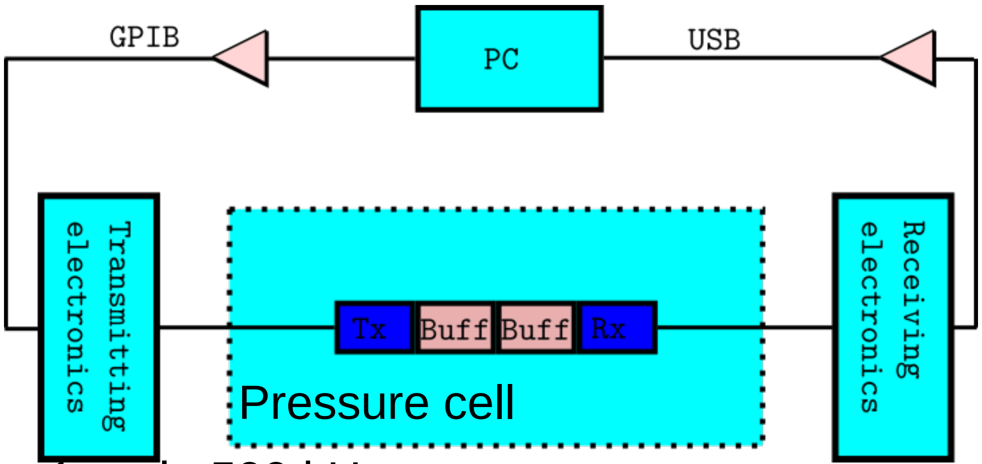
Bentheim sandstone

- Equipment needed to conduct acoustic measurements (solid buffer method)
  - Signal generator, amplifiers, electrical filters, oscilloscope
  - P-wave transducers
  - S-wave transducers

Solid buffer method

Measurement A:

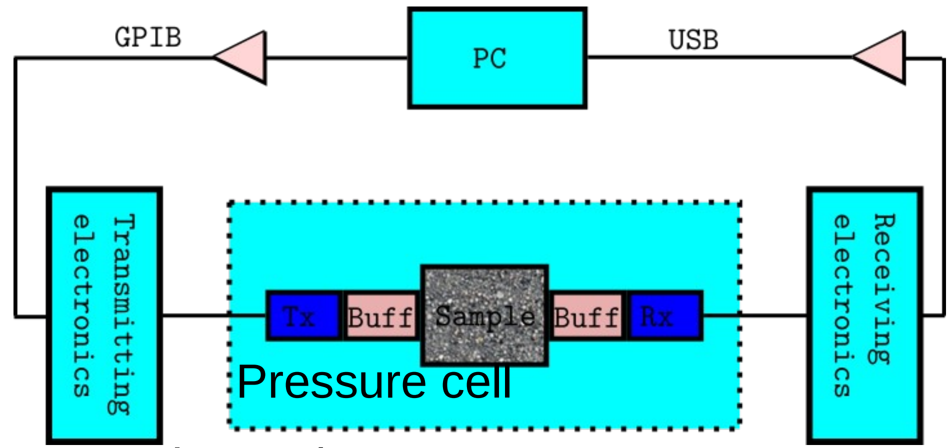
$$t_A = t_{Tel} + t_{Tx} + t_{buff} + t_{buff} + t_{Rx} + t_{Rel}$$



1 cycle 500 kHz

Measurement B:

$$t_B = t_{Tel} + t_{Tx} + t_{buff} + t_{sample} + t_{buff} + t_{Rx} + t_{Rel}$$



1 cycle 500 kHz

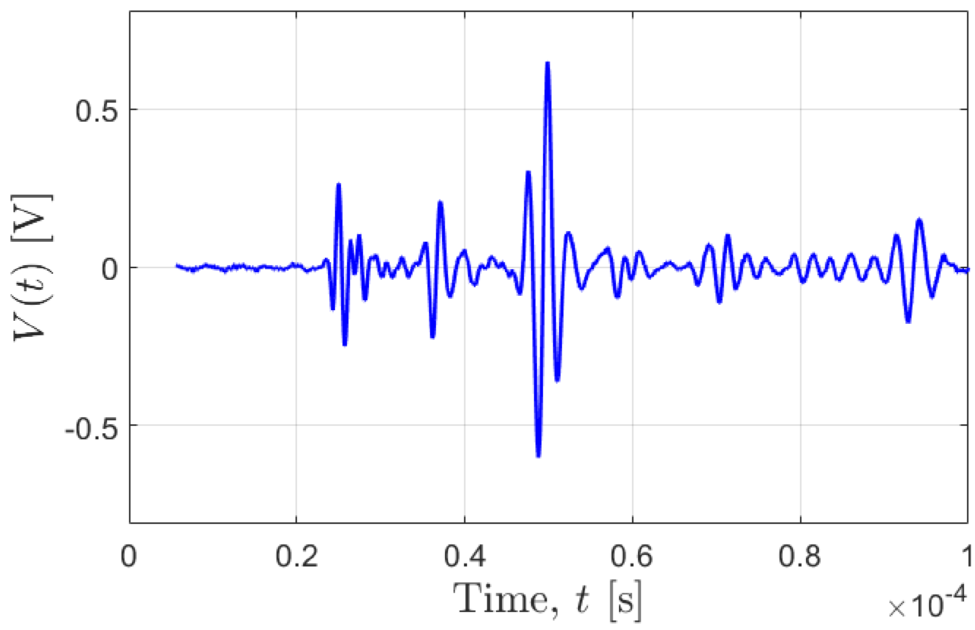
- Elastic wave velocities: Difference between measurement A and B (t_B - t_A)
- Mathematical description depending on signal processing technique

First arrival of the signal

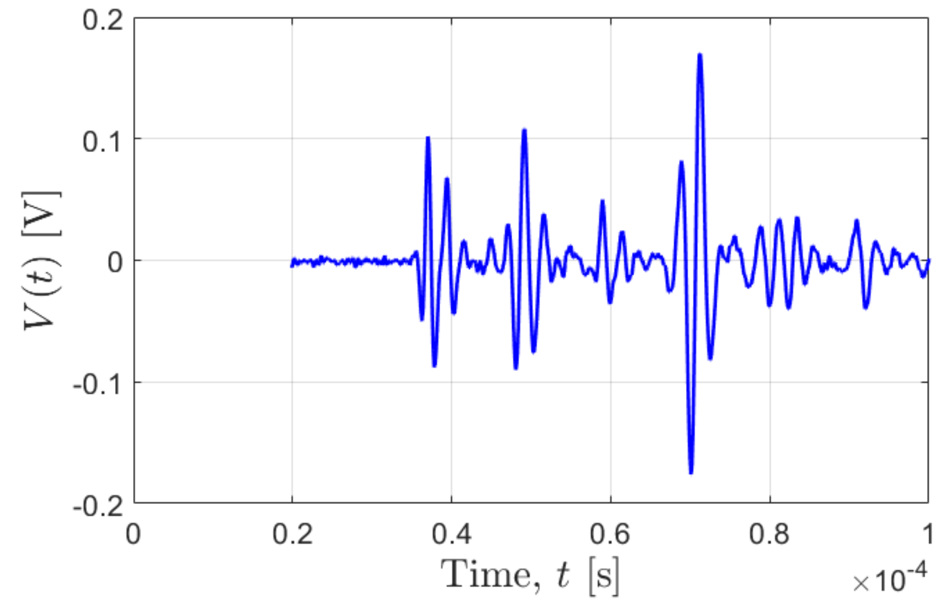
- Shear wave transducers, input signal: 1 cycle, 500 kHz

$$c_S = \frac{d}{t_B - t_A}$$

Measurement A
- Input signal: 0.3 V, 1 cycle, 500 kHz



Measurement B (hydrate bearing sample)
- Input signal: typically 32 V, 1 cycle, 500 kHz



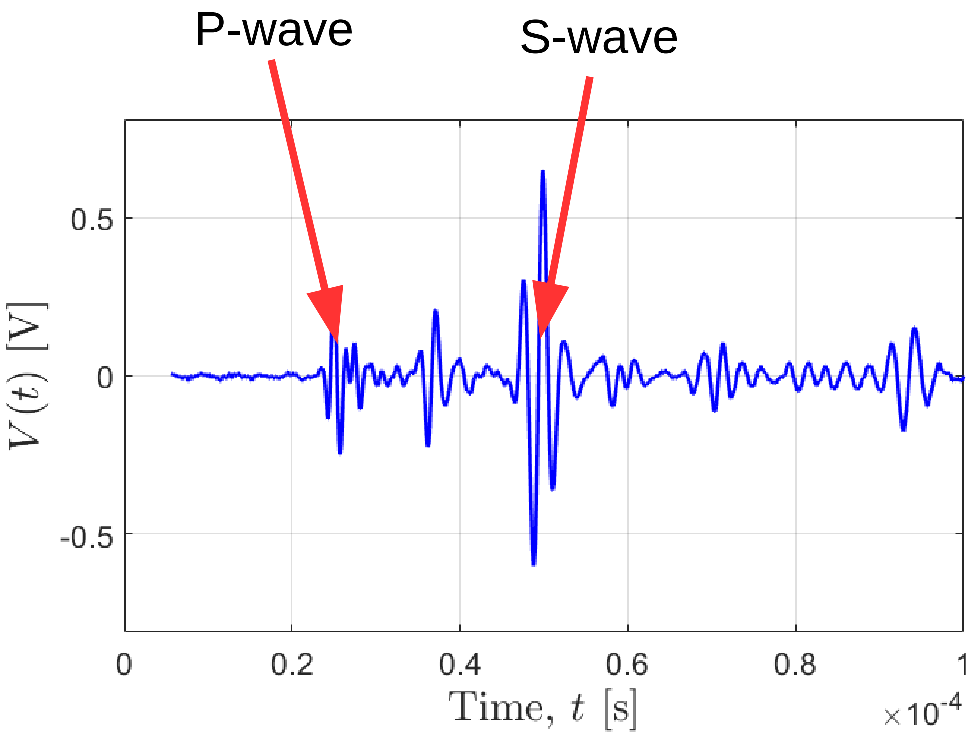
First arrival of the signal

- Shear wave transducers, input signal: 1 cycle, 500 kHz

$$c_S = \frac{d}{t_B - t_A}$$

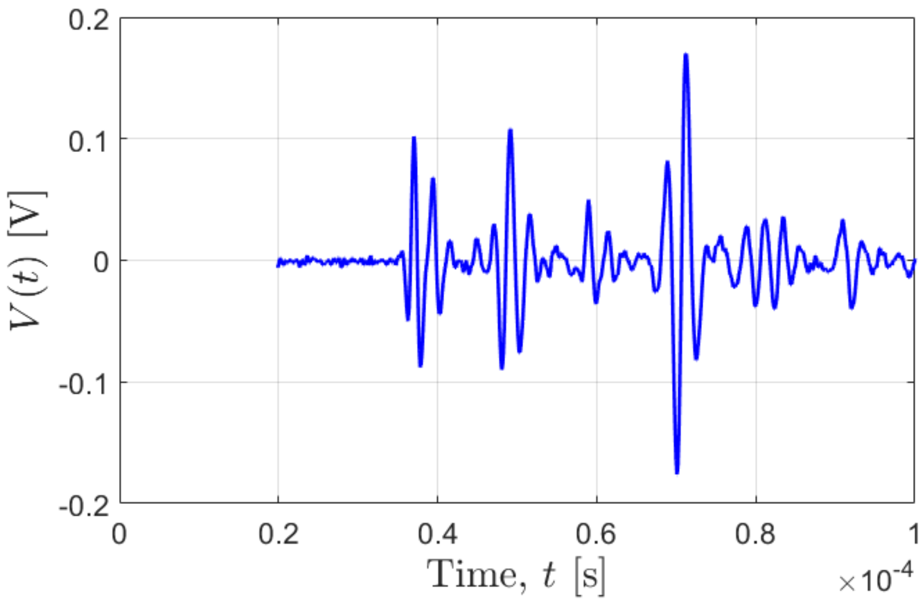
Measurement A

- Input signal: 0.3 V, 1 cycle, 500 kHz



Measurement B (hydrate bearing sample)

- Input signal: typically 32 V, 1 cycle, 500 kHz

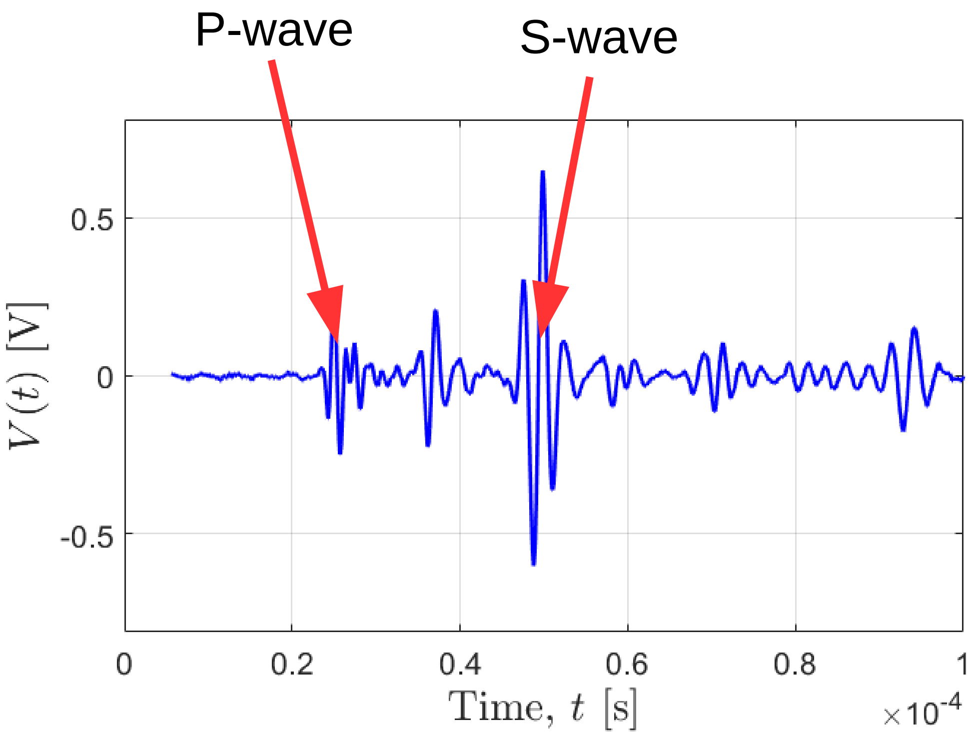


First arrival of the signal

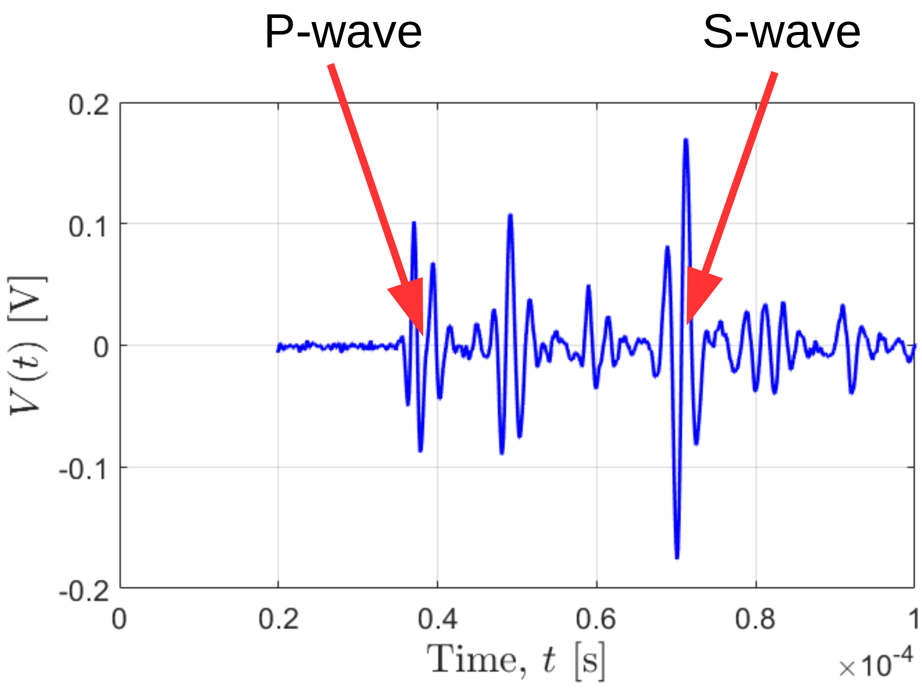
- Shear wave transducers, input signal: 1 cycle, 500 kHz

$$c_S = \frac{d}{t_B - t_A}$$

Measurement A
- Input signal: 0.3 V, 1 cycle, 500 kHz



Measurement B (hydrate bearing sample)
- Input signal: typically 32 V, 1 cycle, 500 kHz

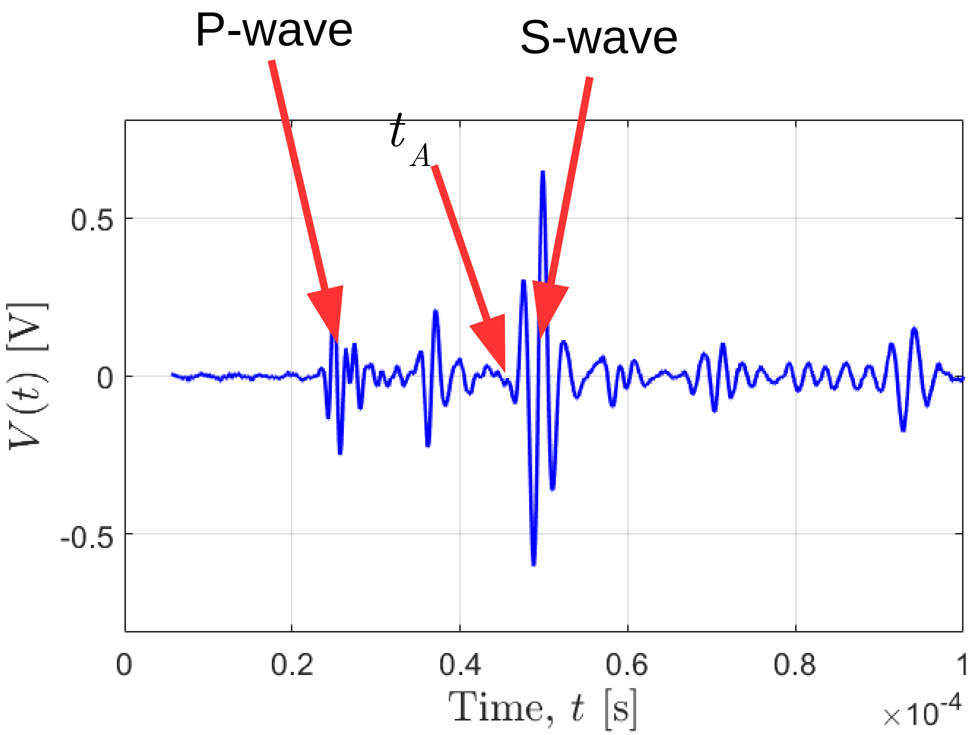


First arrival of the signal

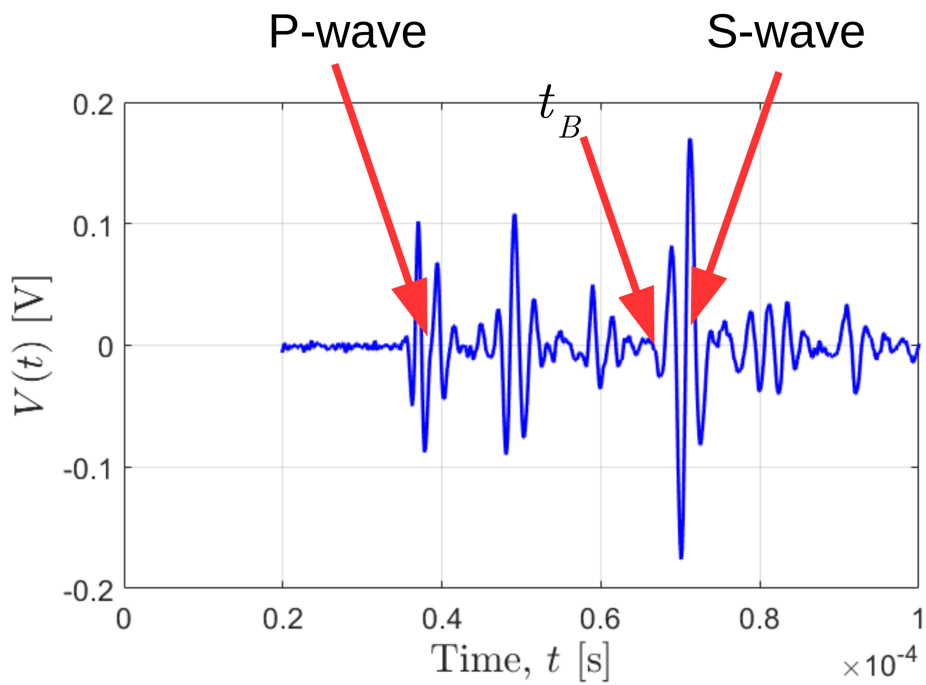
- Shear wave transducers, input signal: 1 cycle, 500 kHz

$$c_S = \frac{d}{t_B - t_A}$$

Measurement A
- Input signal: 0.3 V, 1 cycle, 500 kHz



Measurement B (hydrate bearing sample)
- Input signal: typically 32 V, 1 cycle, 500 kHz

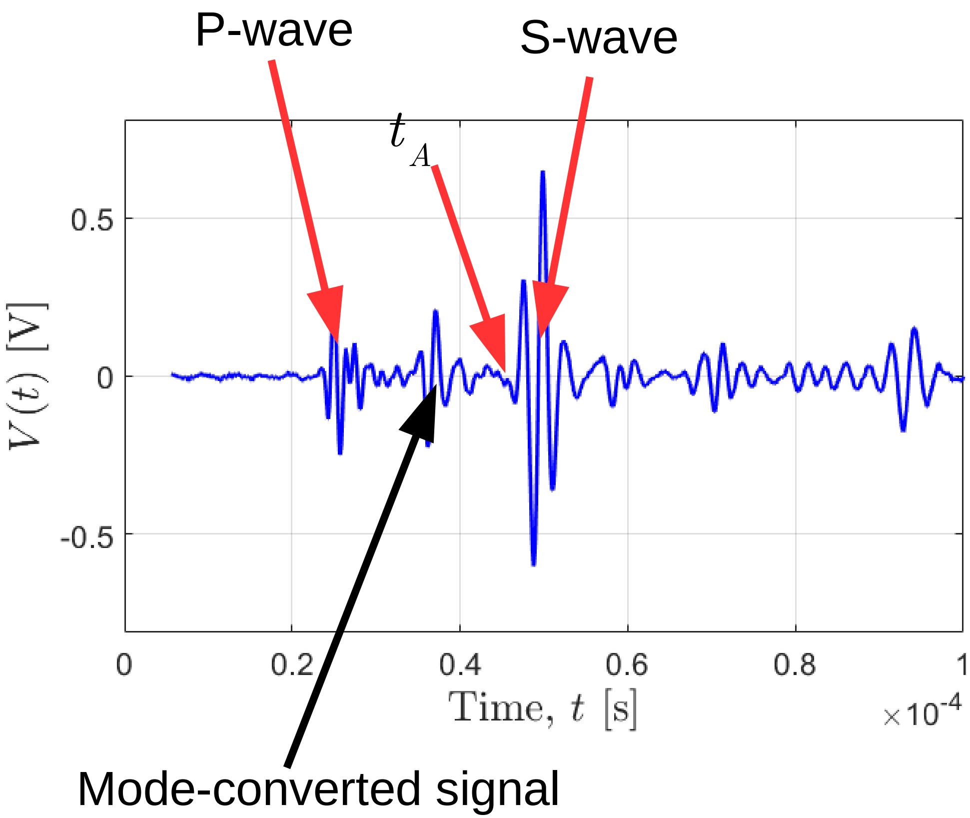


First arrival of the signal

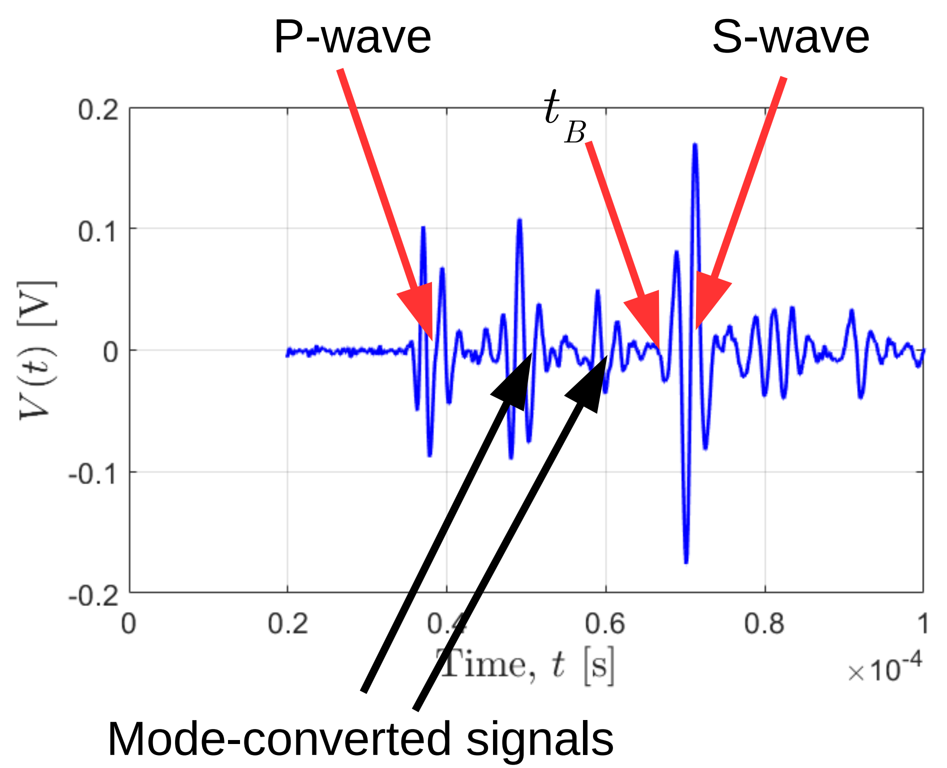
- Shear wave transducers, input signal: 1 cycle, 500 kHz

$$c_S = \frac{d}{t_B - t_A}$$

Measurement A
- Input signal: 0.3 V, 1 cycle, 500 kHz



Measurement B (hydrate bearing sample)
- Input signal: typically 32 V, 1 cycle, 500 kHz

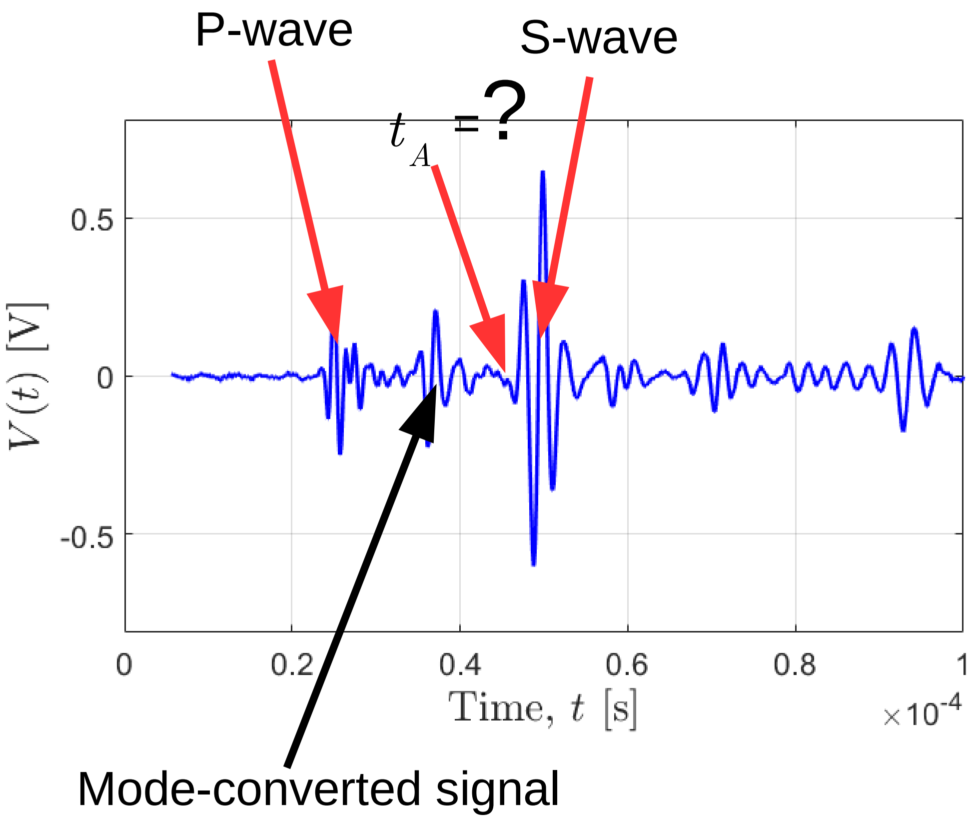


First arrival of the signal

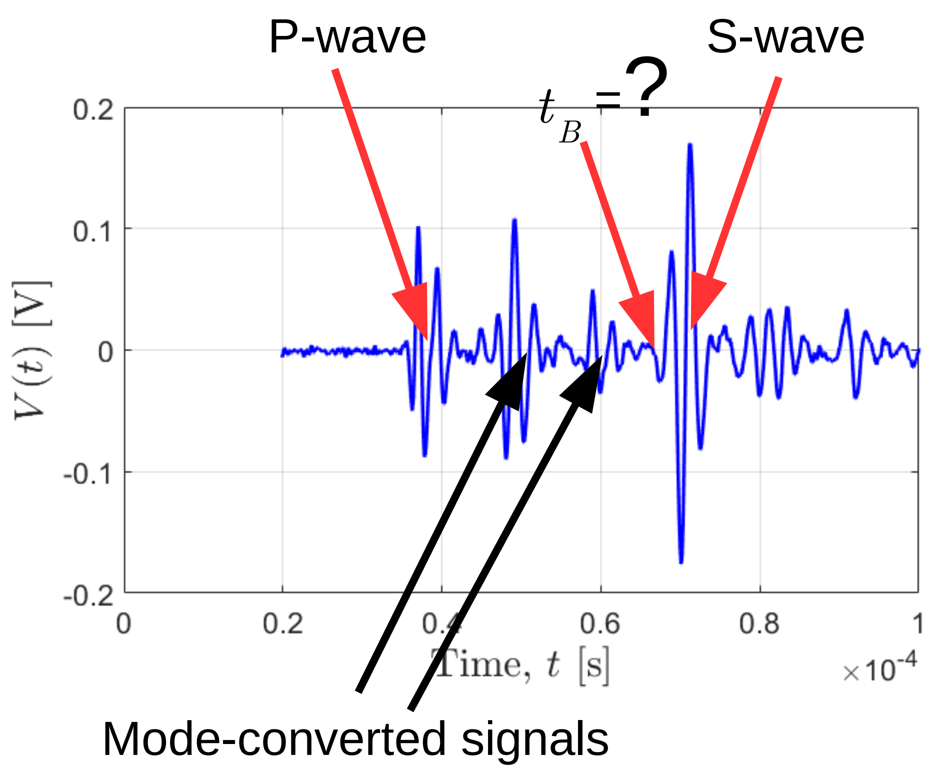
- Shear wave transducers, input signal: 1 cycle, 500 kHz

$$c_S = \frac{d}{t_B - t_A}$$

Measurement A
- Input signal: 0.3 V, 1 cycle, 500 kHz



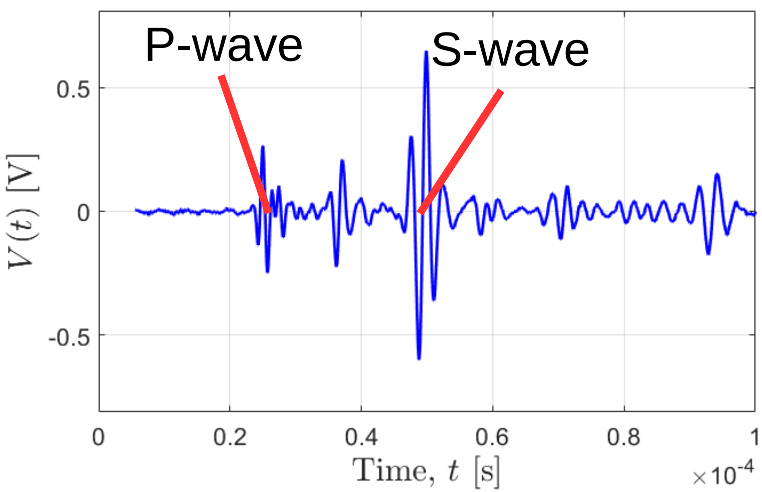
Measurement B (hydrate bearing sample)
- Input signal: typically 32 V, 1 cycle, 500 kHz



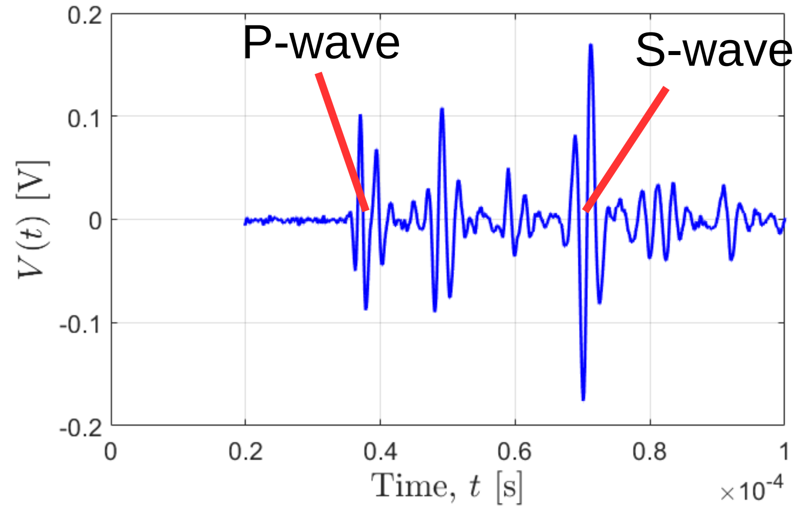
Fourier spectrum signal processing technique[9]

-Shear wave transducers, input signal: 1 cycle 500 kHz

Measurement A



Measurement B (hydrate bearing sample)



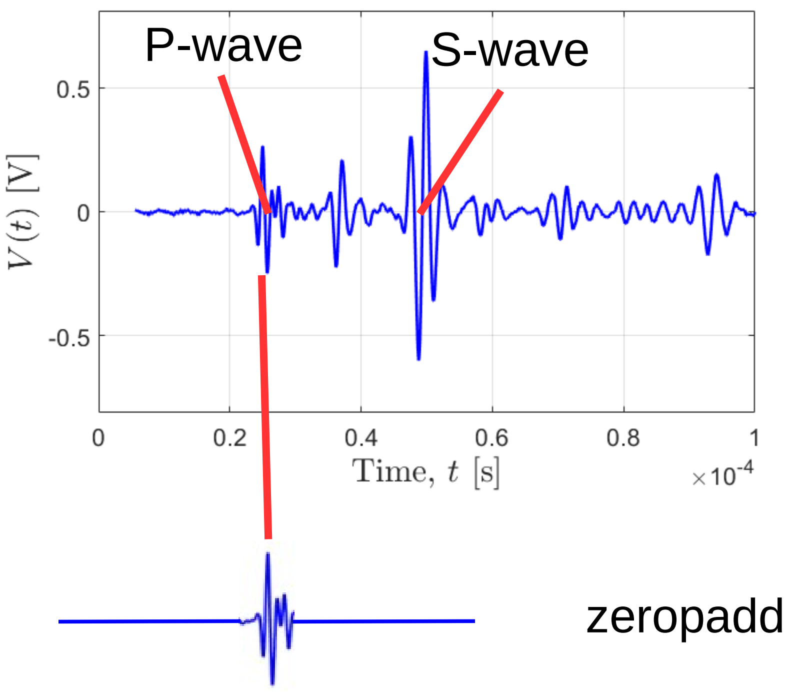
$$c_{P,S} = \frac{d}{\frac{\sphericalangle H(f)_B^{dif} - \sphericalangle H(f)_A^{dif}}{2\pi f} - \frac{\sphericalangle V(f)_B^{event} - \sphericalangle V(f)_A^{event}}{2\pi f}}$$

[9] P. H. Rogers and A. L. Van Buren, “An exact expression for the Lommel-diffraction correction integral”, JASA 55(4), pp. 724–728 (1974).
[10] P. He and J. Zheng, “Acoustic dispersion and attenuation measurement using both transmitted and reected pulses", Ultrasonics 39 (2001)

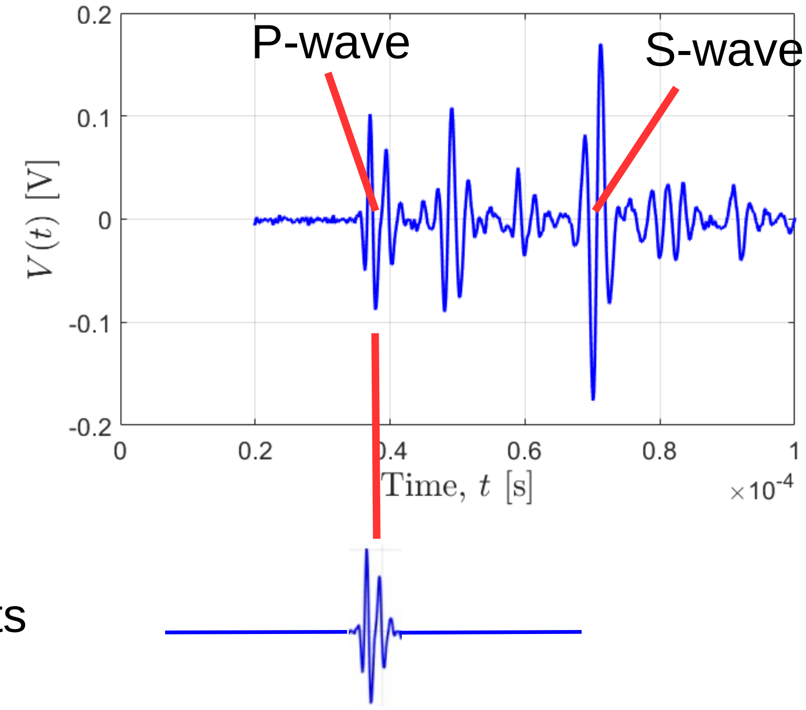
Fourier spectrum signal processing technique[9]

-Shear wave transducers, input signal: 1 cycle 500 kHz

Measurement A



Measurement B (hydrate bearing sample)



zeropadded events

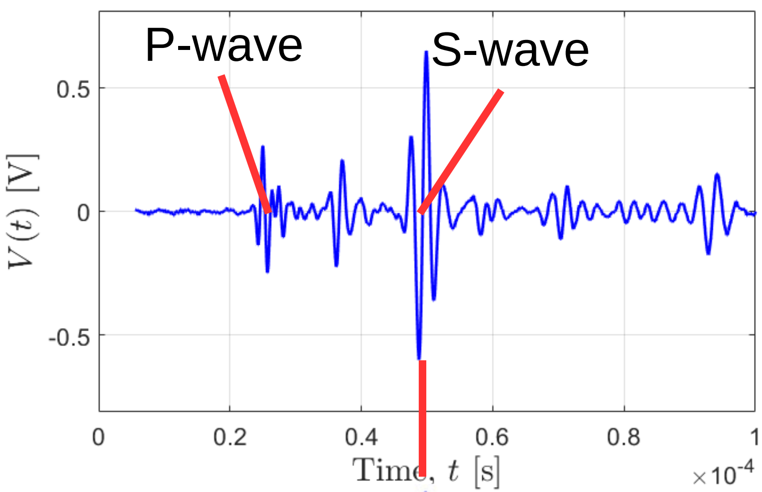
$$c_{P,S}=\frac{d}{\frac{\measuredangle H(f)_B^{dif}-\measuredangle H(f)_A^{dif}}{2\pi f}-\frac{\measuredangle V(f)_B^{event}-\measuredangle V(f)_A^{event}}{2\pi f}}$$

[9] P. H. Rogers and A. L. Van Buren, "An exact expression for the Lommel-diffraction correction integral", JASA 55(4), pp. 724–728 (1974).
[10] P. He and J. Zheng, "Acoustic dispersion and attenuation measurement using both transmitted and reected pulses", Ultrasonics 39 (2001)

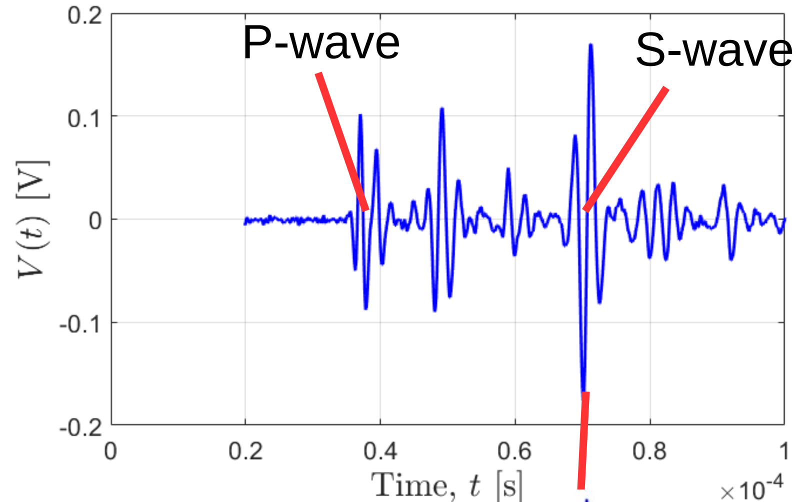
Fourier spectrum signal processing technique[9]

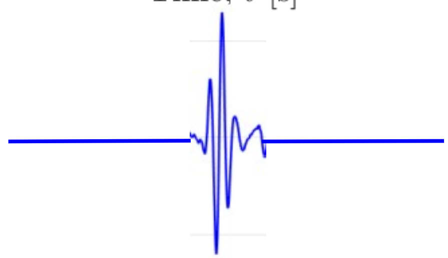
-Shear wave transducers, input signal: 1 cycle 500 kHz

Measurement A

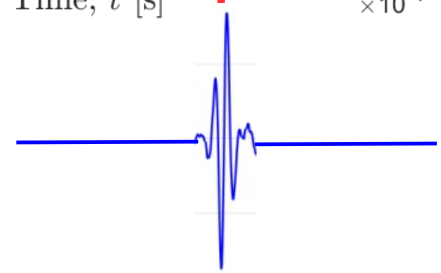


Measurement B (hydrate bearing sample)





zeropadded events



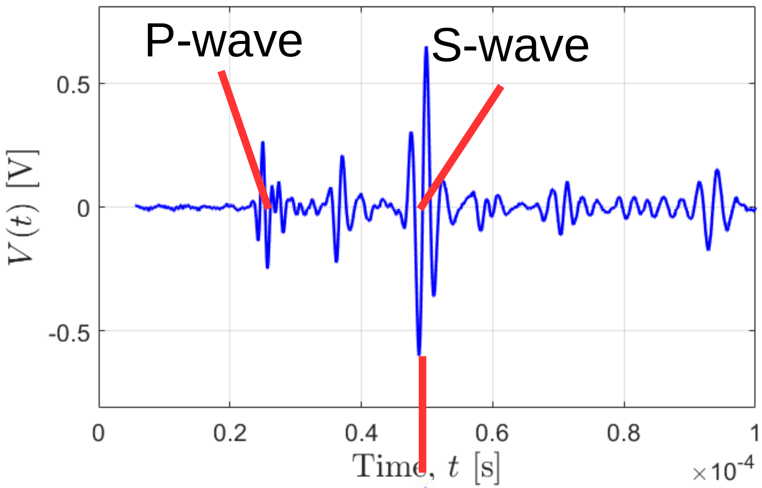
$$c_{P,S}=\frac{d}{\frac{\sphericalangle H(f)_B^{dif}-\sphericalangle H(f)_A^{dif}}{2\pi f}-\frac{\sphericalangle V(f)_B^{event}-\sphericalangle V(f)_A^{event}}{2\pi f}}$$

[9] P. H. Rogers and A. L. Van Buren, “An exact expression for the Lommel-diffraction correction integral”, JASA 55(4), pp. 724–728 (1974).
[10] P. He and J. Zheng, “Acoustic dispersion and attenuation measurement using both transmitted and reected pulses", Ultrasonics 39 (2001)

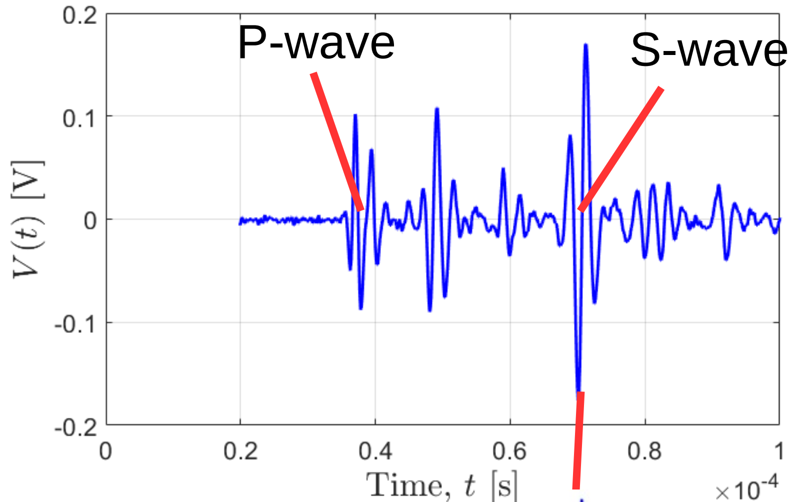
Fourier spectrum signal processing technique[9]

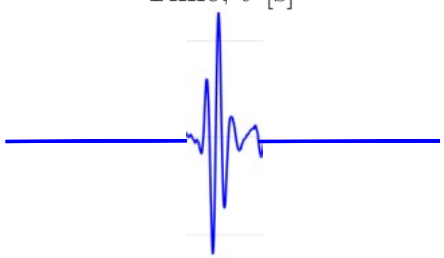
-Shear wave transducers, input signal: 1 cycle 500 kHz

Measurement A

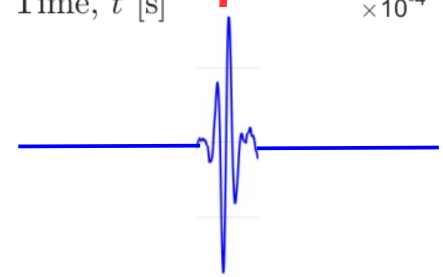


Measurement B (hydrate bearing sample)





zeropadded events



Diffraction correction[9]

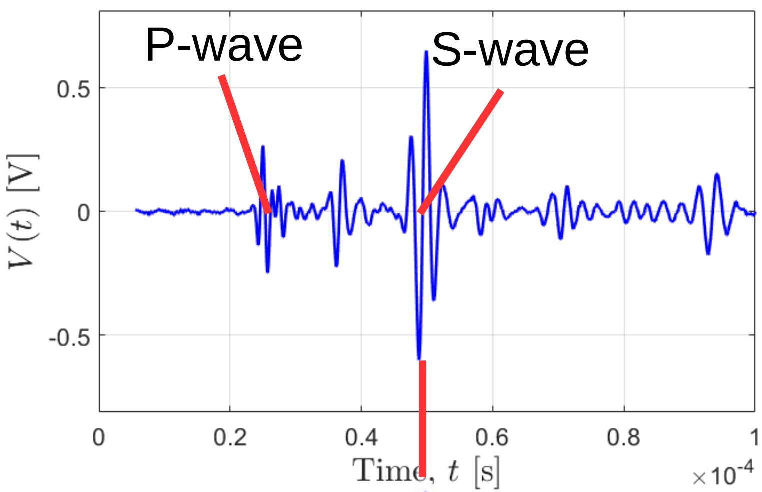
$$c_{P,S} = \frac{d}{\frac{\measuredangle H(f)_B^{dif} - \measuredangle H(f)_A^{dif}}{2\pi f} - \frac{\measuredangle V(f)_B^{event} - \measuredangle V(f)_A^{event}}{2\pi f}}$$

[9] P. H. Rogers and A. L. Van Buren, “An exact expression for the Lommel-diffraction correction integral”, JASA 55(4), pp. 724–728 (1974).
[10] P. He and J. Zheng, “Acoustic dispersion and attenuation measurement using both transmitted and reected pulses", Ultrasonics 39 (2001)

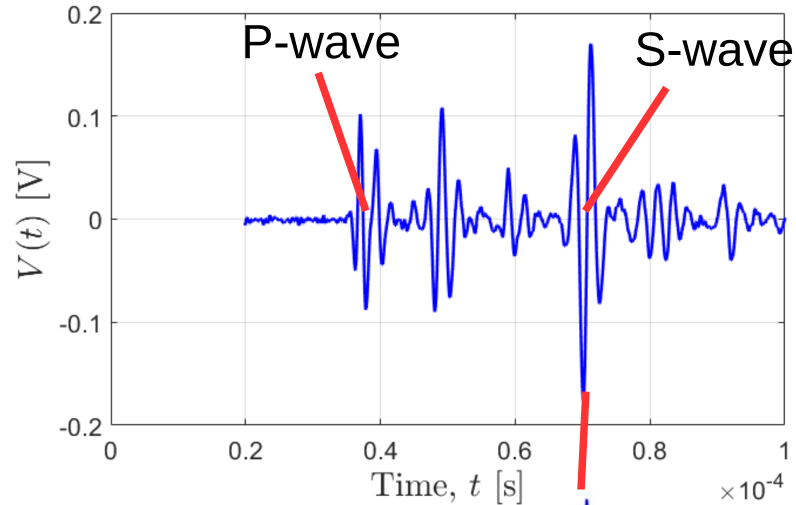
Fourier spectrum signal processing technique[9]

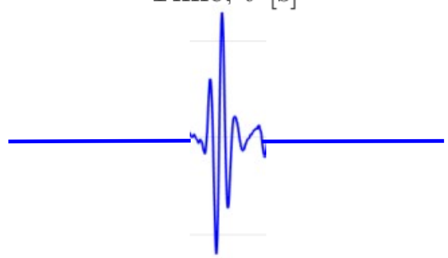
-Shear wave transducers, input signal: 1 cycle 500 kHz

Measurement A

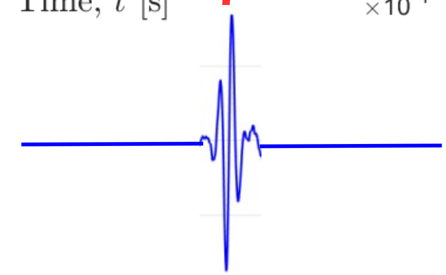


Measurement B (hydrate bearing sample)





zeropadded events



DFT of zeropadded event

$$c_{P,S} = \frac{d}{\dfrac{\sphericalangle H(f)_B^{dif} - \sphericalangle H(f)_A^{dif}}{2\pi f} - \dfrac{\sphericalangle V(f)_B^{event} - \sphericalangle V(f)_A^{event}}{2\pi f}}$$

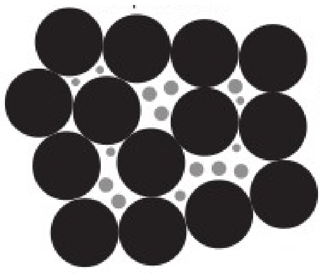
[9] P. H. Rogers and A. L. Van Buren, “An exact expression for the Lommel-diffraction correction integral”, JASA 55(4), pp. 724–728 (1974).

[10] P. He and J. Zheng, “Acoustic dispersion and attenuation measurement using both transmitted and reected pulses", Ultrasonics 39 (2001)

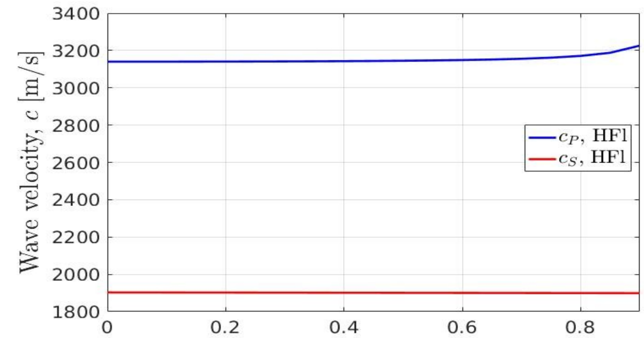
Outline

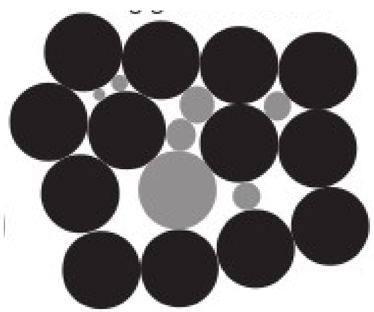
- Motivation
- Experimental setup and measurement method
  - Pressure cell
  - Solid buffer method
  - Fourier spectrum and first arrival of pulse signal processing techniques
- Methane hydrate measurements and modelling
  - Numerical models
  - Elastic wave velocities
- Conclusions and further work

Numerical models and hydrate growth patterns

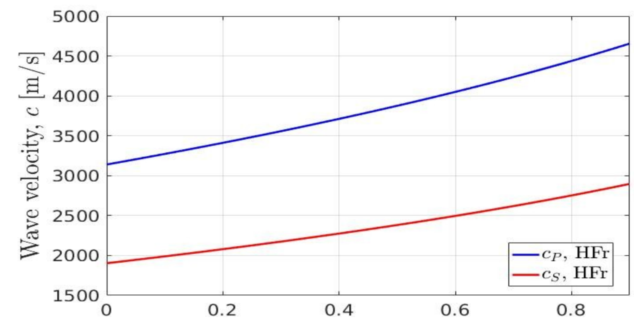


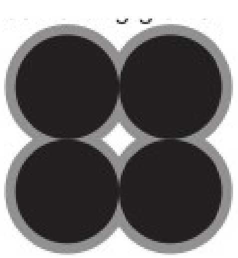
Hydrates in fluid, “HFl”
(Helgerud et al. 1999)



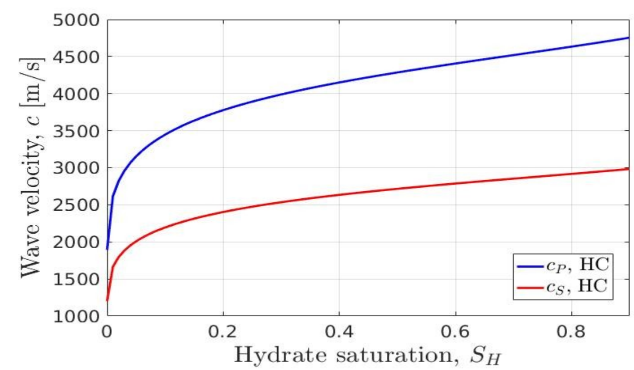


Hydrates in frame, “HFr”
(Helgerud et al. 1999)





Hydrates cementing, “HC”
(Avset et al. 2000,
Dvorkin et al. 1994)

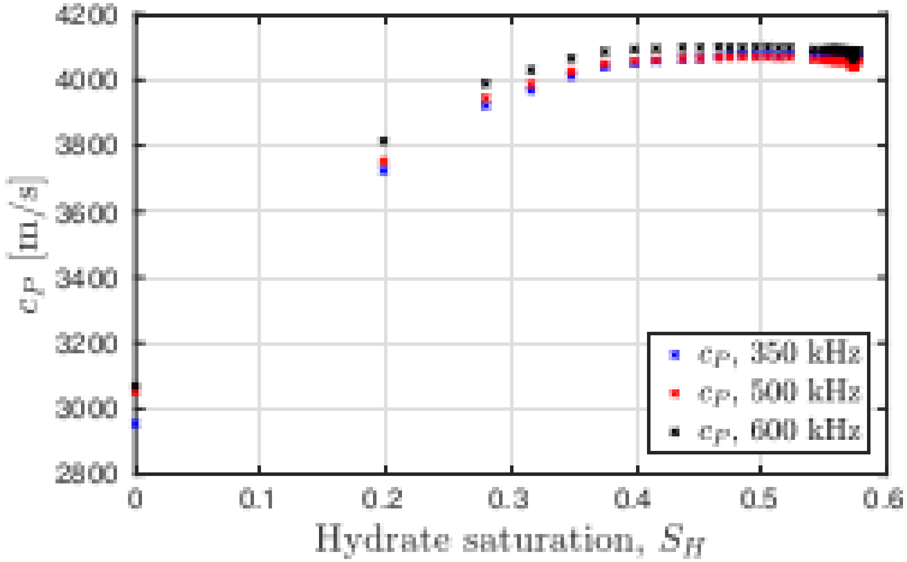


[11] M. Helgerud, J. Dvorkin, A. Nur, A. Sakai, and T. Collett, “Elastic-wave velocity in marine sediments with gas hydrates: Effective medium modeling”, Geophysical Research Letters 26(13), pp. 2021–2024 (1999).
[12] P. Avseth, J. Dvorkin, G. Mavko, and J. Rykkje, “Rock physics diagnostic of North Sea sands: Link between microstructure and seismic properties”, Geophysical Research Letters 27(17), pp. 2761–2764 (2000).
[13] J. Dvorkin, A. Nur, and H. Yin, “Effective properties of cemented granular materials”, Mechanics of materials 18(4), pp. 351–366 (1994).

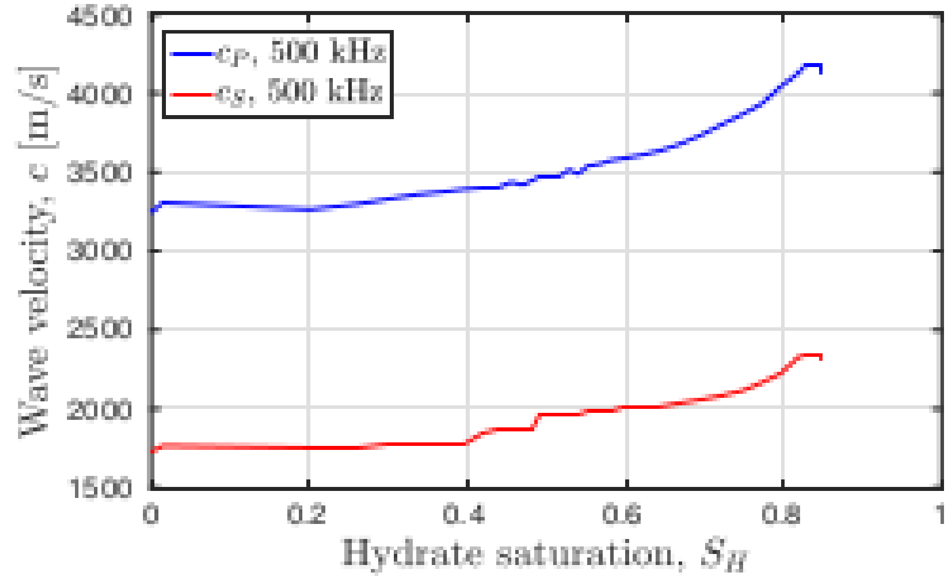
c_P and c_S during hydrate growth

- Measurements and numerical models

Experiment 1: S_{w0} = 0.48.
P-waves: Frequency 350-600 kHz

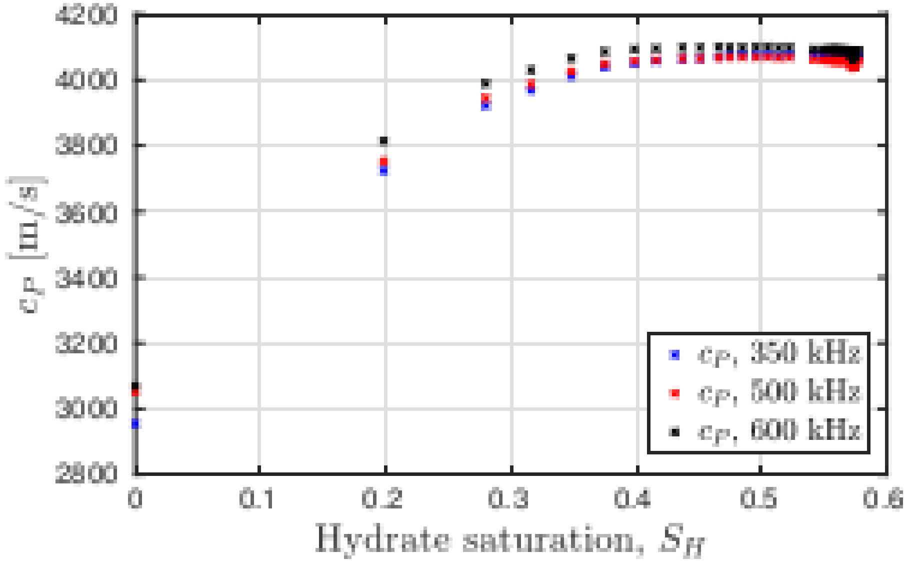


Experiment 10: S_{w0} = 0.95
P and S-waves: Frequency 500 kHz



c_P and c_S during hydrate growth
- Measurements and numerical models

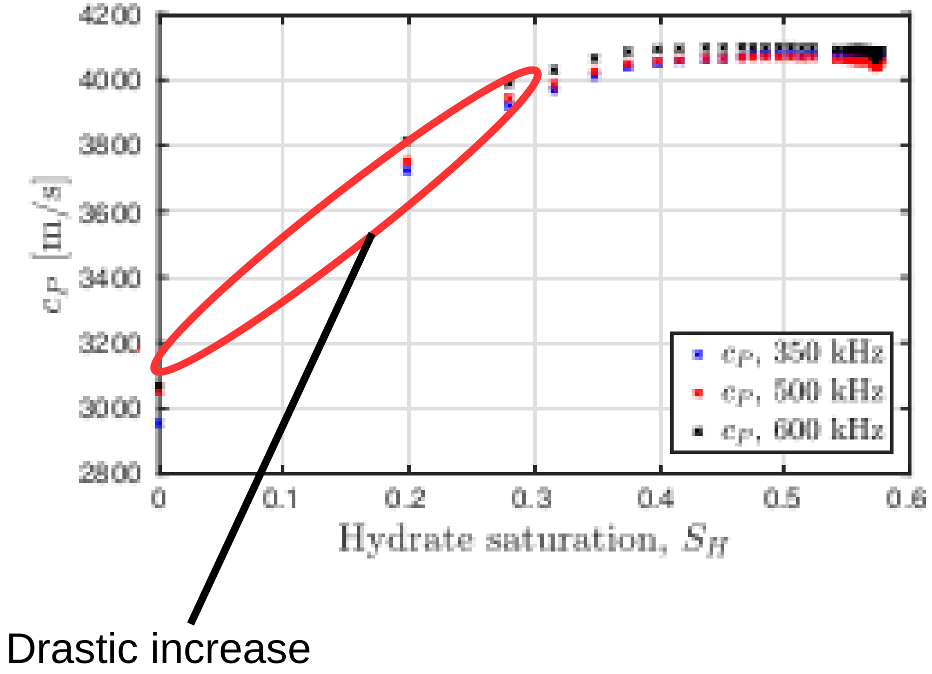
Experiment 1: S_{w0} = 0.48.
P-waves: Frequency 350-600 kHz



c_P and c_S during hydrate growth

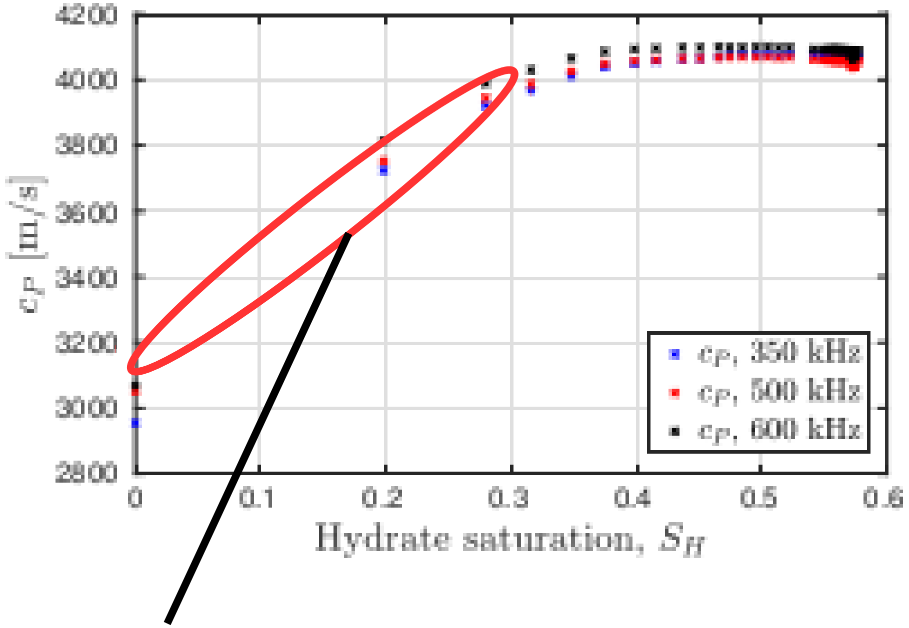
- Measurements and numerical models

Experiment 1: S_{w0} = 0.48.
P-waves: Frequency 350-600 kHz

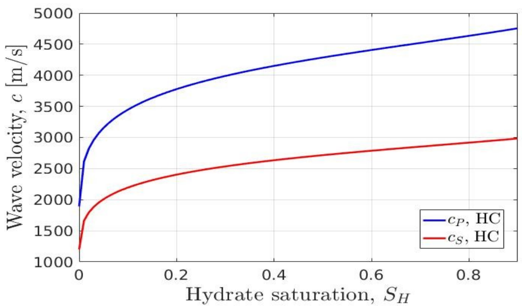


c_P and c_S during hydrate growth
- Measurements and numerical models

Experiment 1: S_{w0} = 0.48.
P-waves: Frequency 350-600 kHz



Drastic increase
Hydrate partially cementing grains?

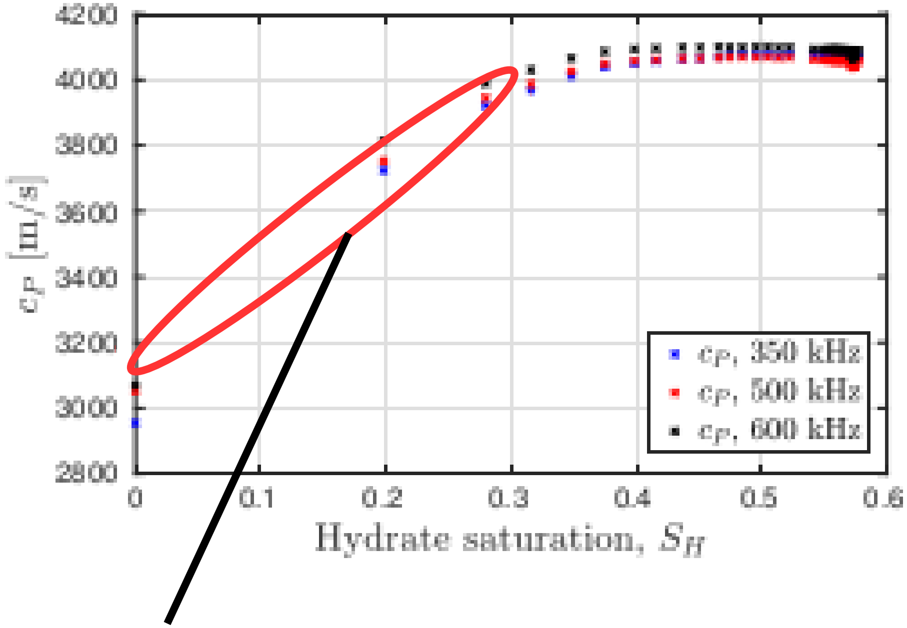


"HC"-model

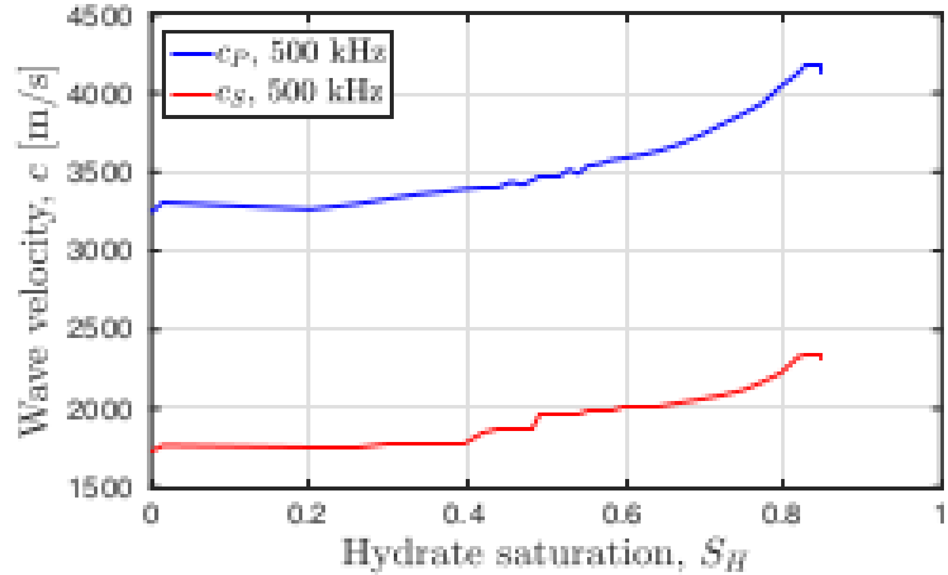
c_P and c_S during hydrate growth

- Measurements and numerical models

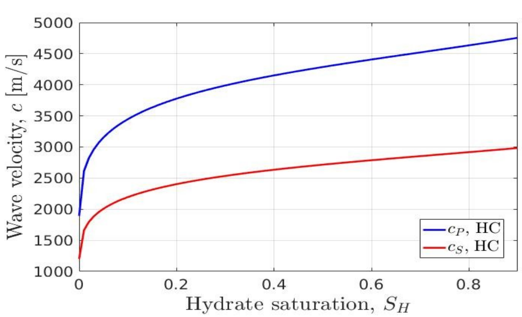
Experiment 1: S_{w0} = 0.48.
P-waves: Frequency 350-600 kHz



Experiment 10: S_{w0} = 0.95
P and S-waves: Frequency 500 kHz



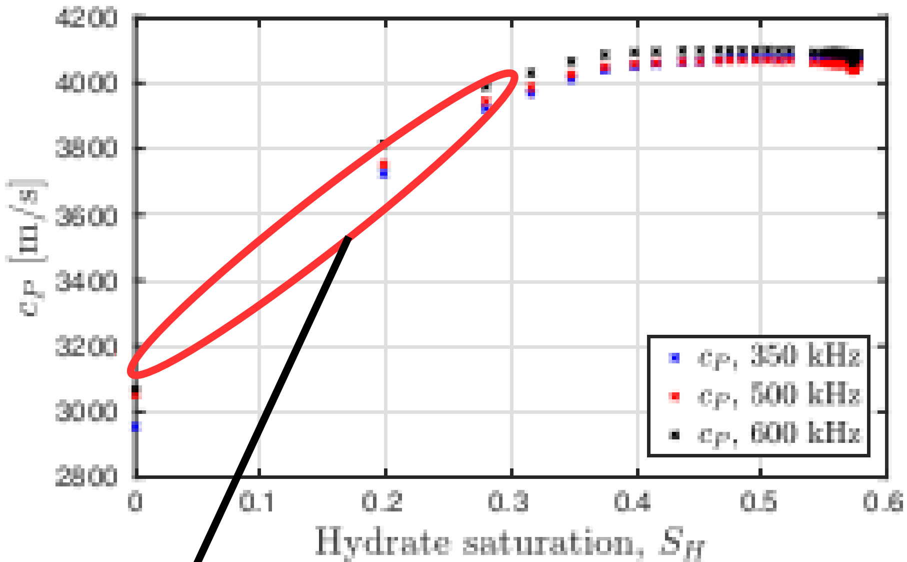
Drastic increase
Hydrate partially cementing grains?



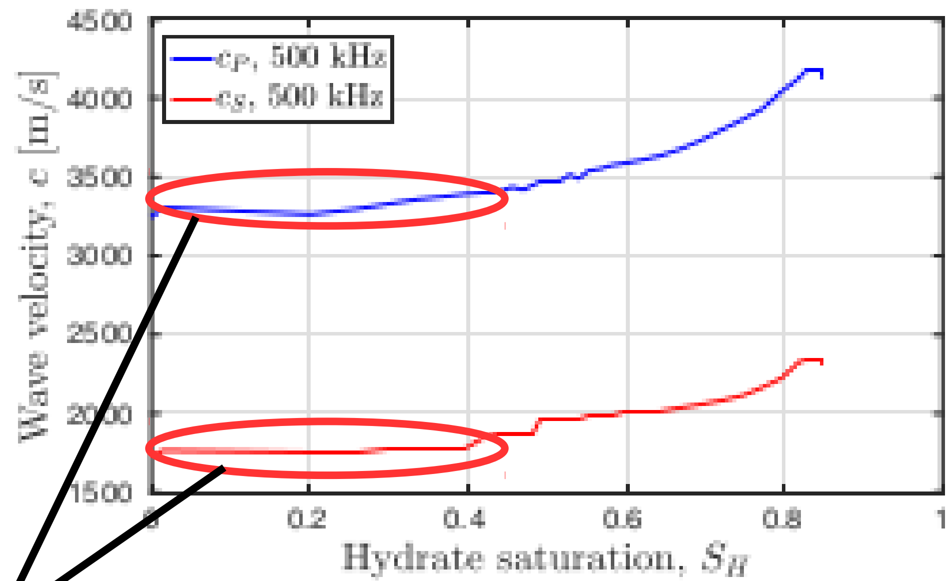
“HC”-model

c_P and c_S during hydrate growth
- Measurements and numerical models

Experiment 1: S_{w0} = 0.48.
P-waves: Frequency 350-600 kHz

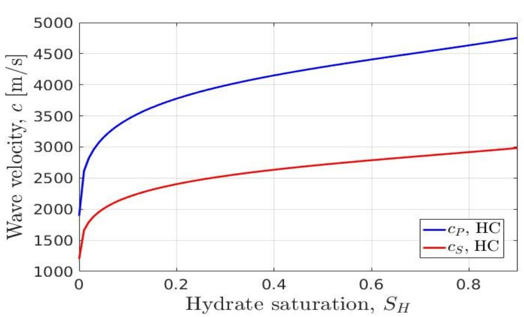


Experiment 10: S_{w0} = 0.95
P and S-waves: Frequency 500 kHz



Drastic increase
Hydrate partially cementing grains?

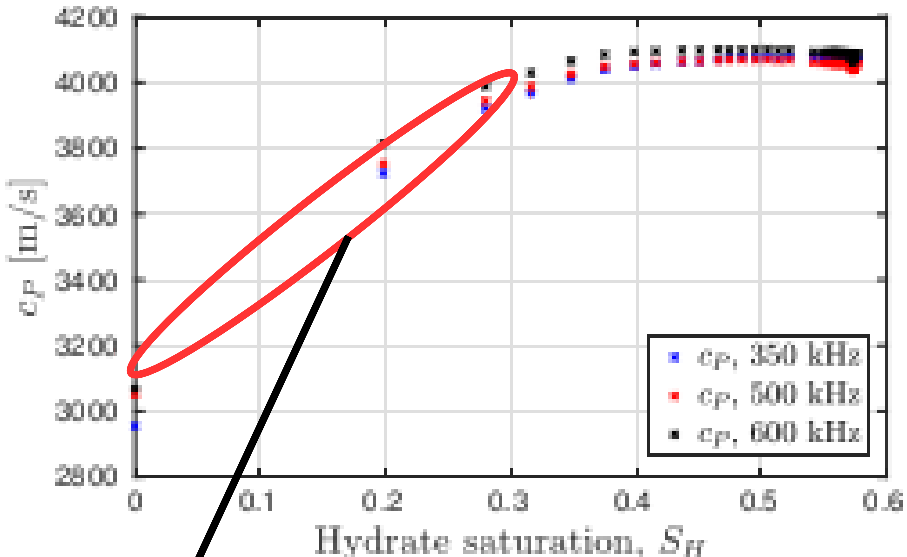
No increase



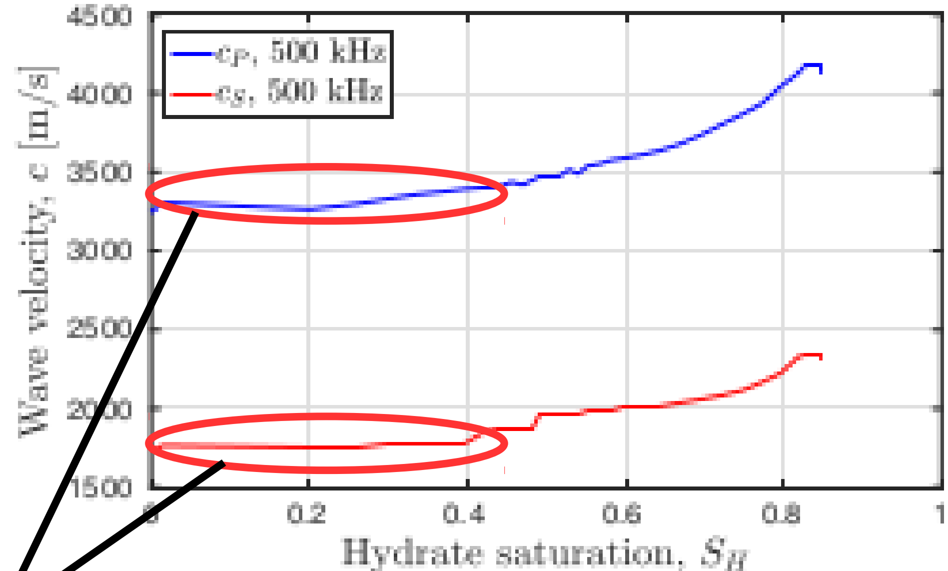
"HC"-model

c_P and c_S during hydrate growth
- Measurements and numerical models

Experiment 1: S_{w0} = 0.48.
P-waves: Frequency 350-600 kHz

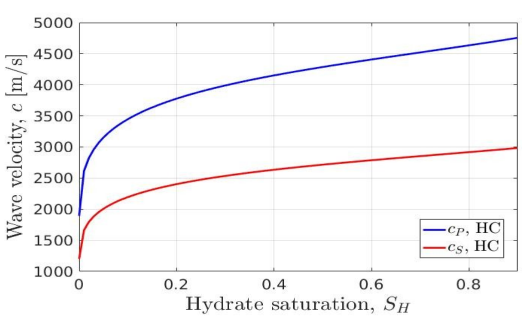


Experiment 10: S_{w0} = 0.95
P and S-waves: Frequency 500 kHz

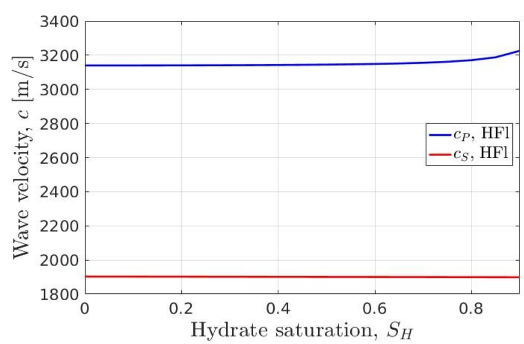


Drastic increase
Hydrate partially cementing grains?

No increase
Hydrate forming in fluid?



"HC"-model

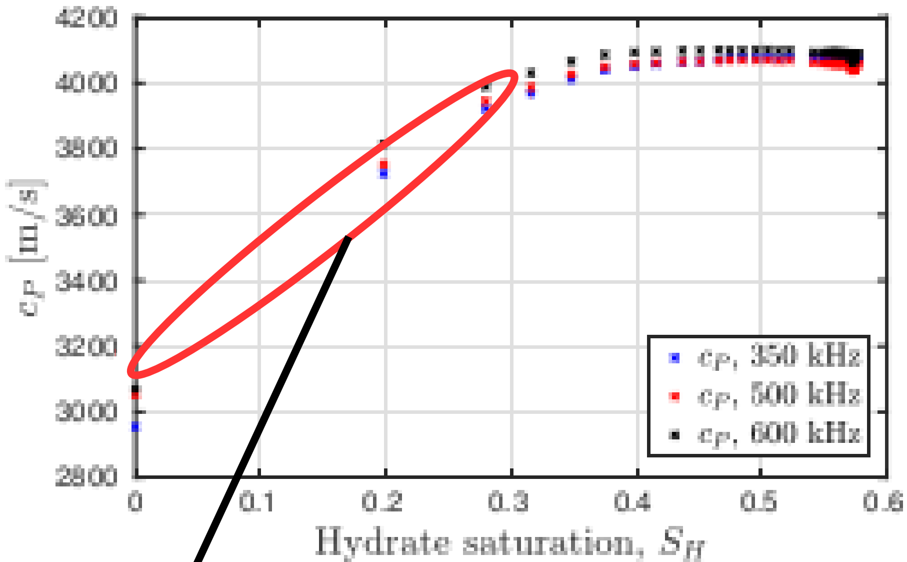


"HFI"-model

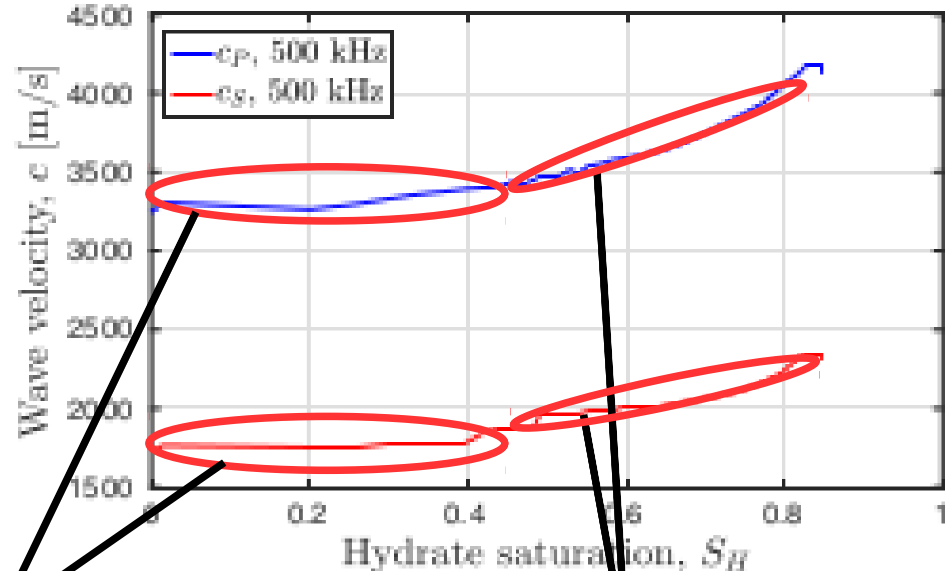
c_P and c_S during hydrate growth

- Measurements and numerical models

Experiment 1: S_{w0} = 0.48.
P-waves: Frequency 350-600 kHz



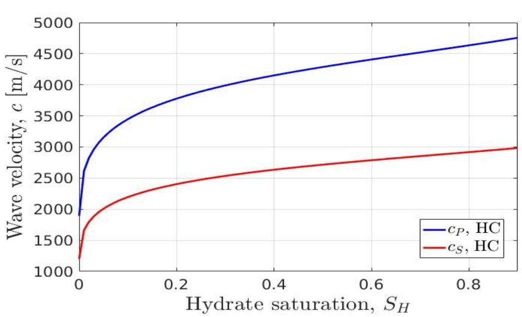
Experiment 10: S_{w0} = 0.95
P and S-waves: Frequency 500 kHz



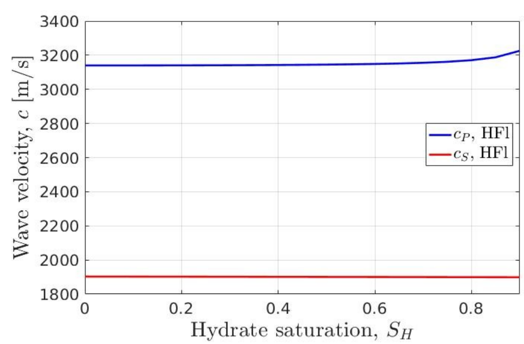
Drastic increase
Hydrate partially cementing grains?

No increase
Hydrate forming in fluid?

Some increase



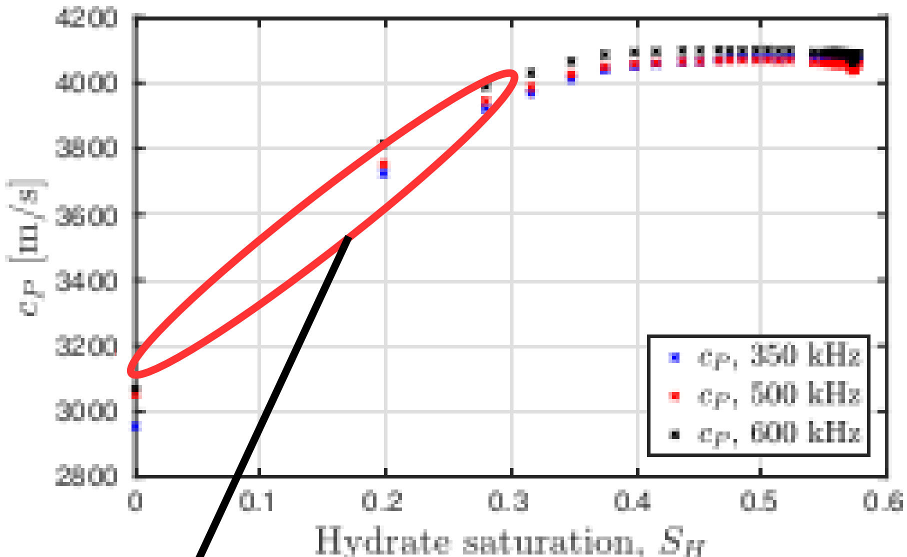
“HC”-model



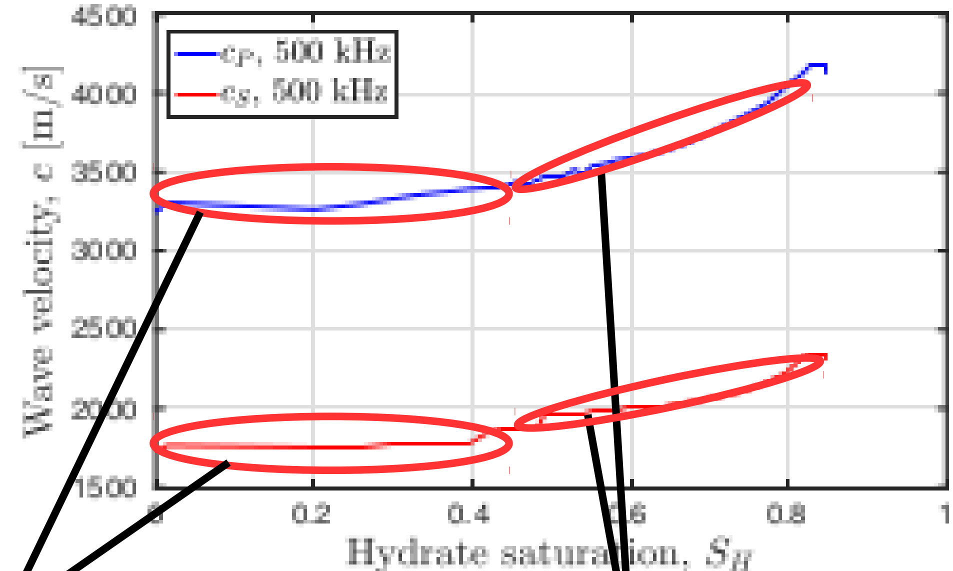
“HFl”-model

c_P and c_S during hydrate growth
- Measurements and numerical models

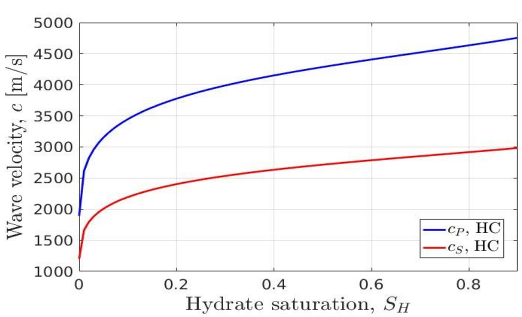
Experiment 1: S_{w0} = 0.48.
P-waves: Frequency 350-600 kHz



Experiment 10: S_{w0} = 0.95
P and S-waves: Frequency 500 kHz

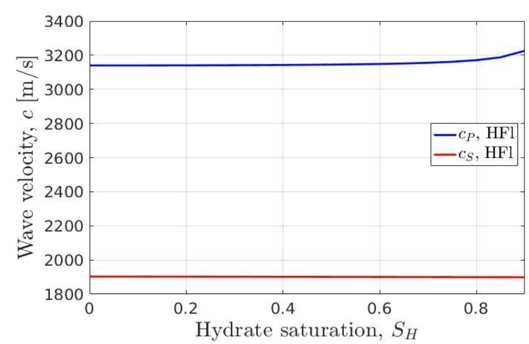


Drastic increase
Hydrate partially cementing grains?



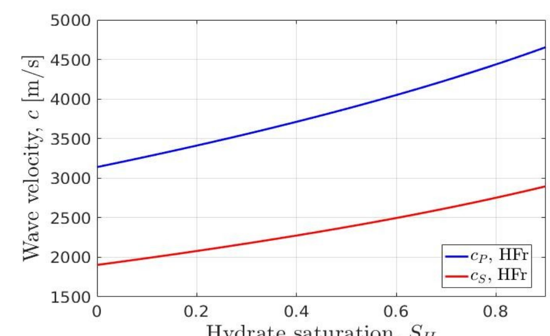
"HC"-model

No increase
Hydrate forming in fluid?



"HFl"-model

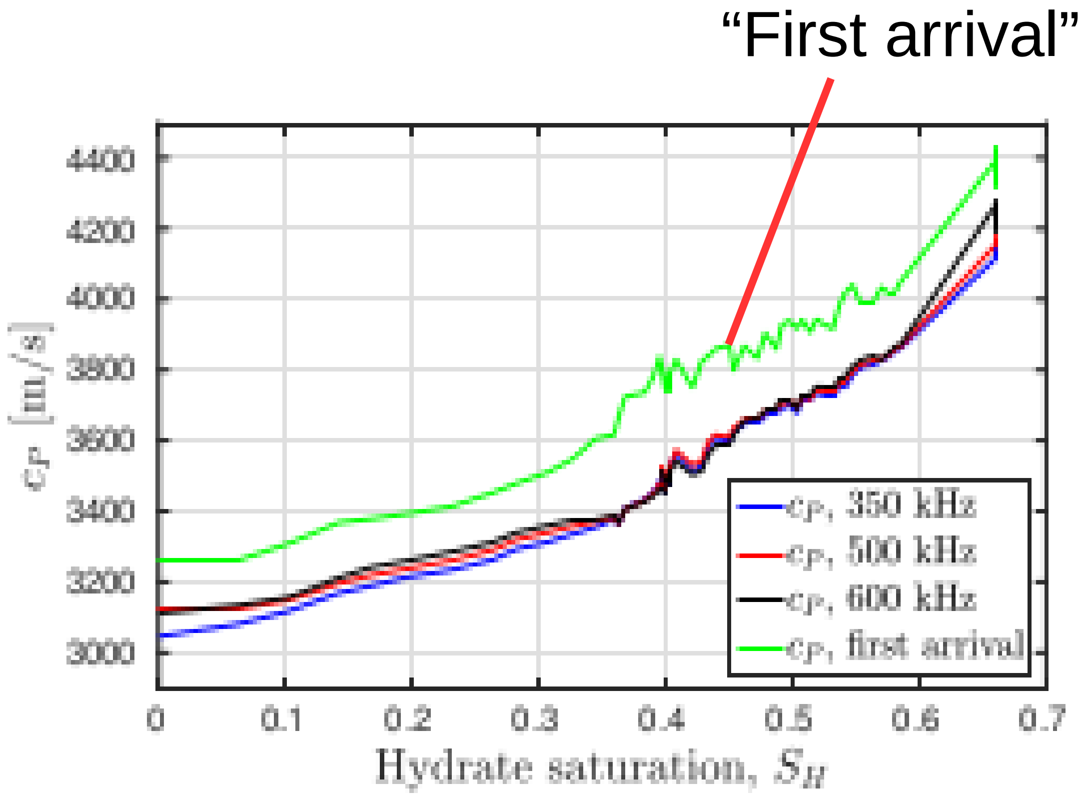
Some increase
Hydrate growing in frame?



"HFr"-model

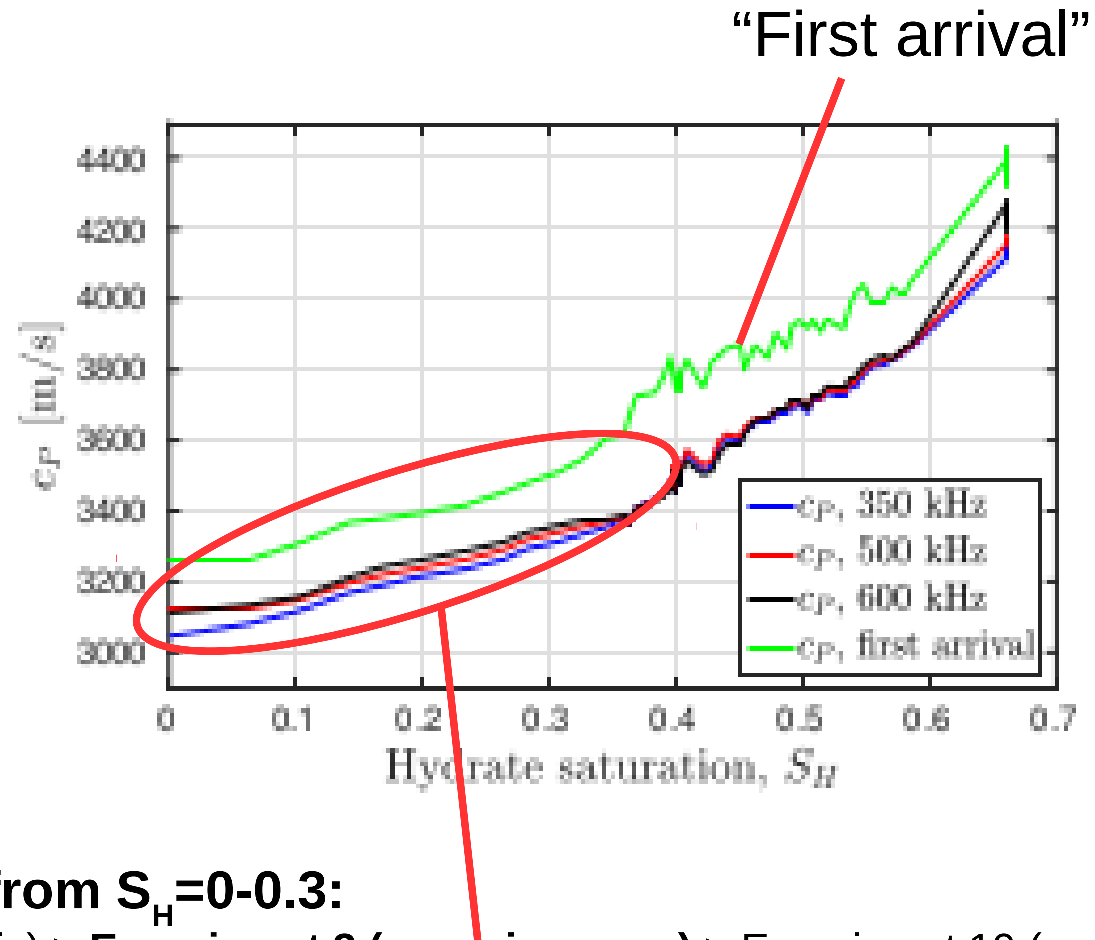
First arrival of the pulse vs. Fourier spectrum method

Experiment 3: S_{w0} = 0.65



First arrival of the pulse vs. Fourier spectrum method

Experiment 3: S_{w0} = 0.65



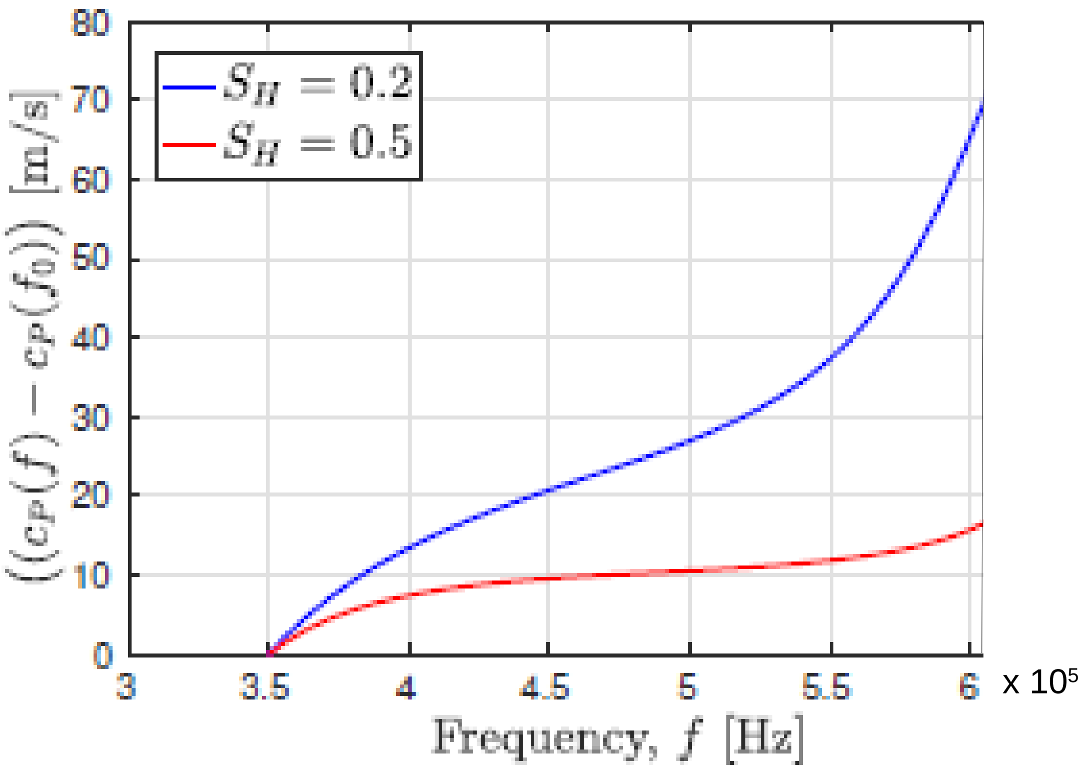
Increase in c_P from S_H=0-0.3:

Experiment 1 (drastic) > **Experiment 3 (some increase)** > Experiment 10 (no increase)
(S_{w0} = 0.48) **(S_{w0} = 0.65)** (S_{w0} = 0.95)

Dispersion for experiment 3 during hydrate growth

Experiment 3

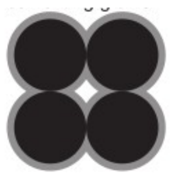
Dispersion curves c_P relative to 350 kHz

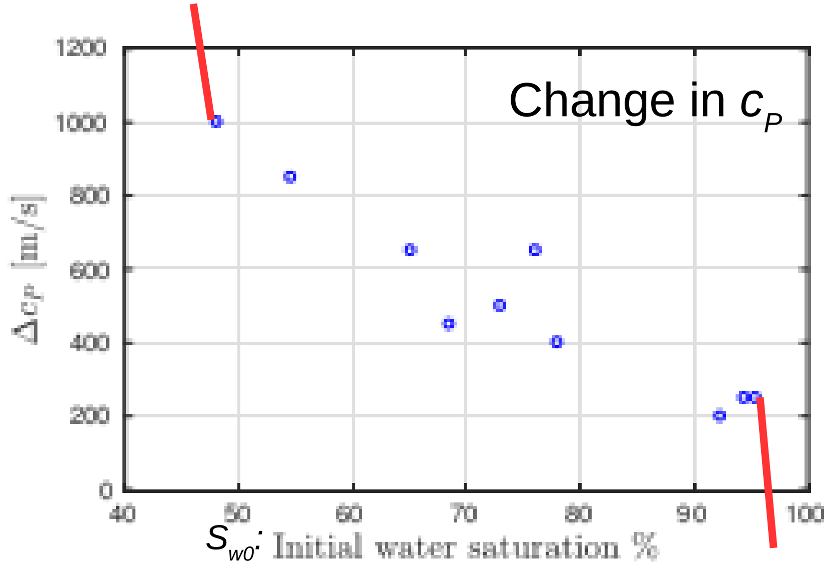


Increase in elastic wave velocities as a function of S_{w0}
-Summary, experiments 1-10

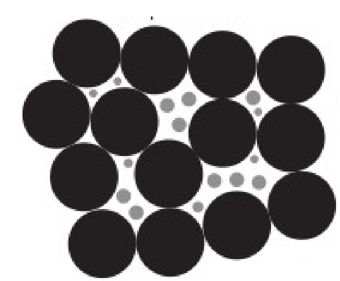
- $\Delta c_p = c_p(S_H=0.5) - c_p(S_H=0)$, at 500 kHz

Experiment 1 ($S_{w0}=0.48$)
Hydrates acting as cement?





Experiment 10 ($S_{w0}=0.95$)
Hydrates forming in the fluid?



- Consistent with other studies [2,7]

Conclusions and further work

- Conclusions
  - Fourier spectrum method
    - S_{w0} low: Hydrates acting as cement or as load bearing grains
    - S_{w0} high: Hydrates forming in the pore fluid
    - Consistent with other studies
  - First arrival of pulse signal processing technique: Higher measured c_P
  - Less dispersion after hydrate growth
- Further work
  - Numerical models with loss incorporated
  - Sonic and ultrasonic frequencies?

Acknowledgment

- Acoustics group (Dept. of physics and technology UiB)
- Professor Morten Jacobsen (Dept. of earth science UiB)
- Professor Tor Arne Johansen (Dept. of earth science UiB)
- Professor Arne Graue (Dept. of physics and technology UiB)