Computational Modeling of Acoustic-Solid Interaction for Early Kick Detection in Wellbores Using Logging-While-Drilling (LWD) Tools

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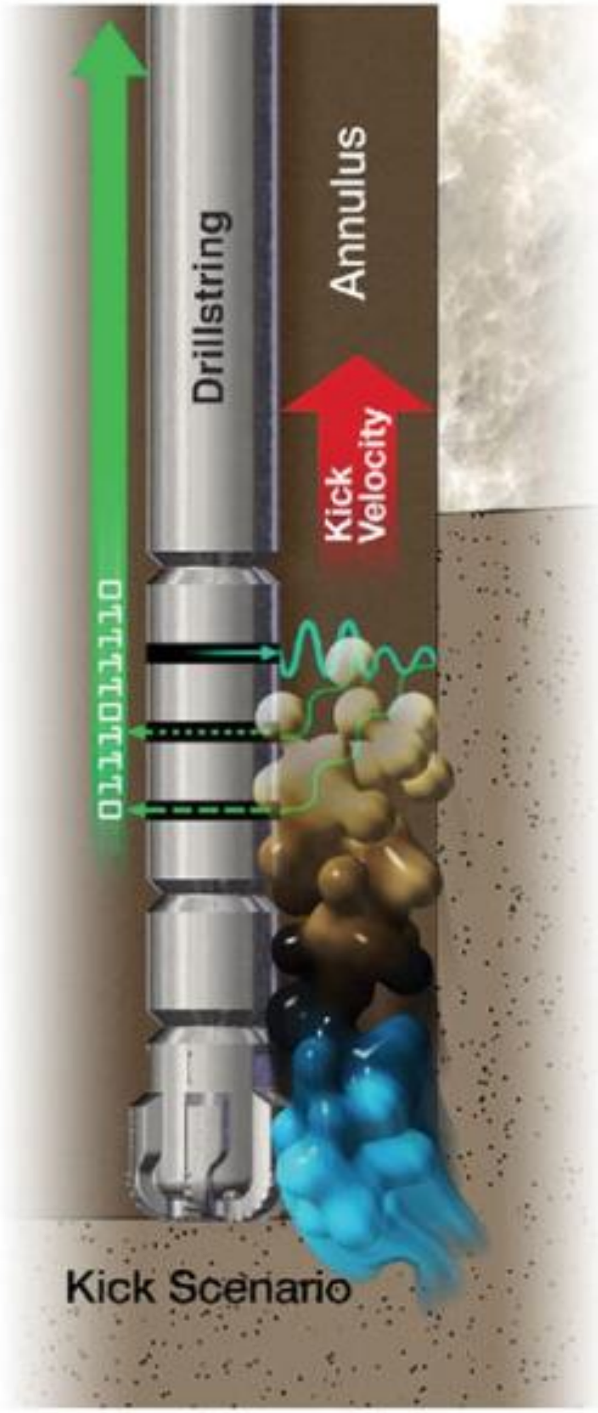
August 2nd, 2023



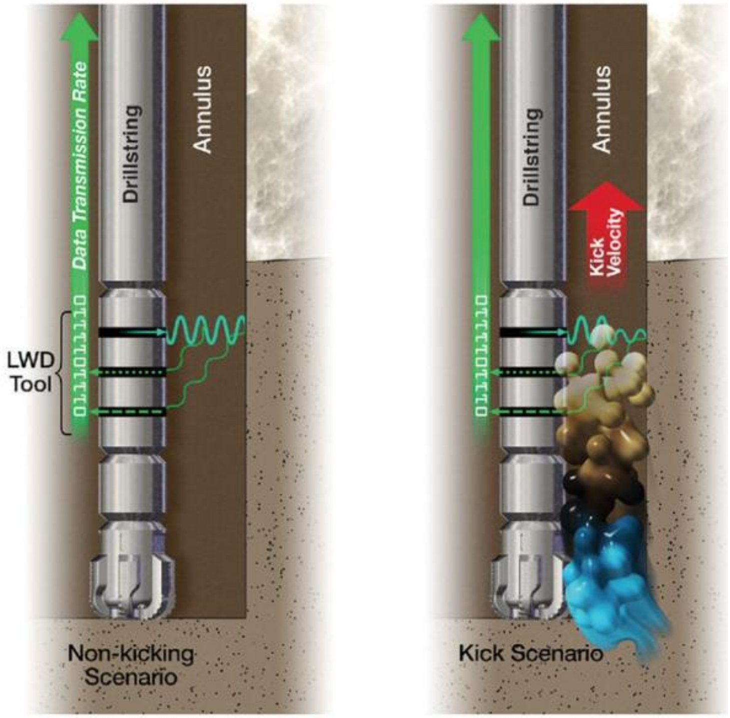
Motivation: Early Kick Detection (EKD)

Unexpected gas invasion (kick) into the borehole is a persistent threat during drilling. Traditional kick detection has a significant time lag (hours) and is affected by missed and false detection.

Gas influx can result in a loss of well control and/or blowouts. Accurate Early Kick Detection (EKD) is crucial to improvement in well control safety.

Deepwater Horizon explosion in Louisiana's Gulf of Mexico on April 20, 2010 (Photo: US coast guard)

The suggested method for **Early Kick Detection (EKD)** involves utilizing geophysical signals from **Logging-While-Drilling (LWD)** sensors, enabling real-time detection within minutes[2,3].



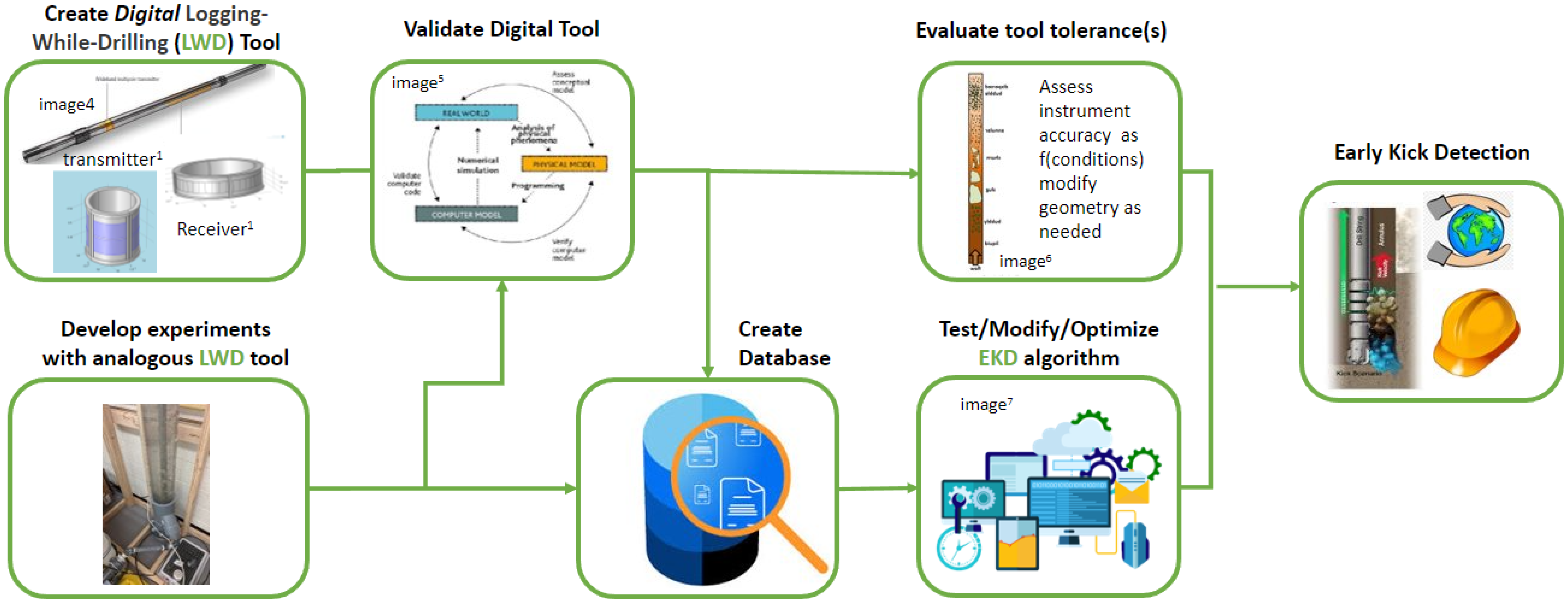
- Field and laboratory data are scarce and not easily accessible.
- Unlocking Valuable Data in Wellbore Dynamics
- Produce a comprehensive multiphase flow dataset to support advanced EKD

2) Rose, K., et. al., 2019, USPO #10253620;
3) Adapted from Tost, B., et. al., 2016, ttps://doi.org/10.2172/1327810

Method Overview / Objectives

- The main methodology is based on combining experimental and numerical acoustic simulation to generate synthetic data and develop an EKD algorithm.

- **Produce synthetic data** to help fill the knowledge gap and to aid in Early Kick Detection (EKD) algorithm development



1) Jiang, et al., Proceedings of the 2014 COMSOL Conference in Boston, Understanding Logging-While-Drilling Transducers with COMSOL Multiphysics® Software; 4) Alford, et al., Oilfield Review Spring 2012: 24, no. 1.; 5) Lapuerta, C., et al., Nuclear Eng. And Design, 2012, 253, https://doi.org/10.1016/j.nucengdes.2011.09.068; 6) **Unalmis, O. H., 2015,** doi: 10.1121/2.0000069; 7) web: Custom Advisory Group http://www.customeradvisorygroup.com/grc---process-control-implementations.html

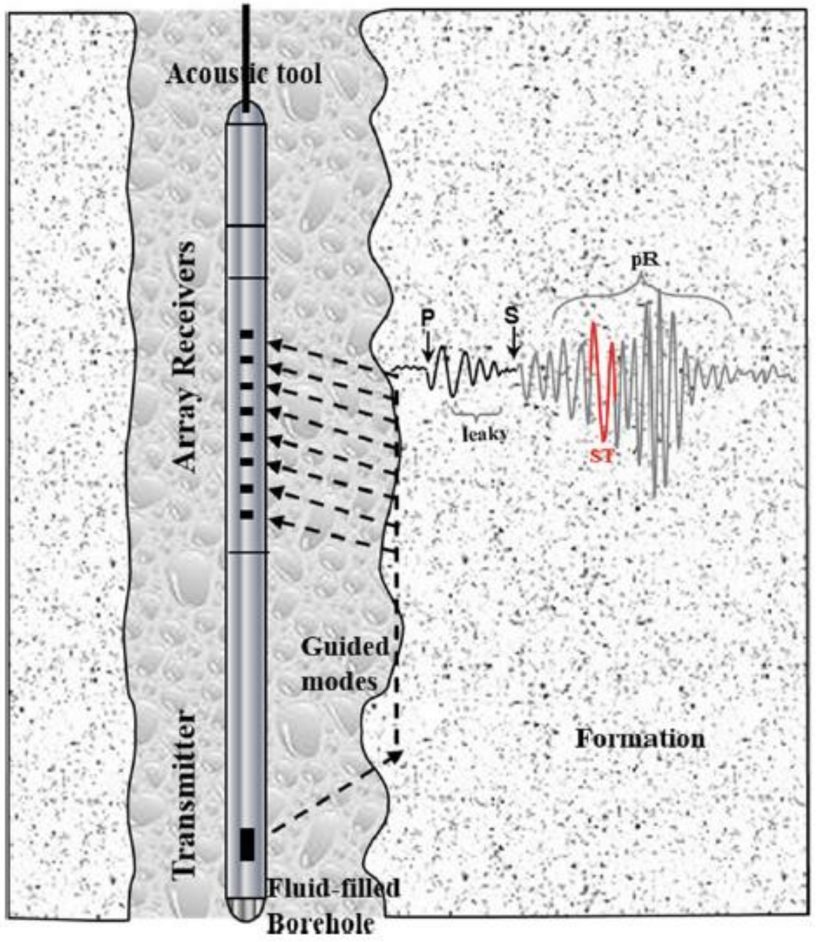
Wellbore Acoustic Modeling

LWD Sonic tool sends a signal

The acoustic wave travels through the fluid to the rock.

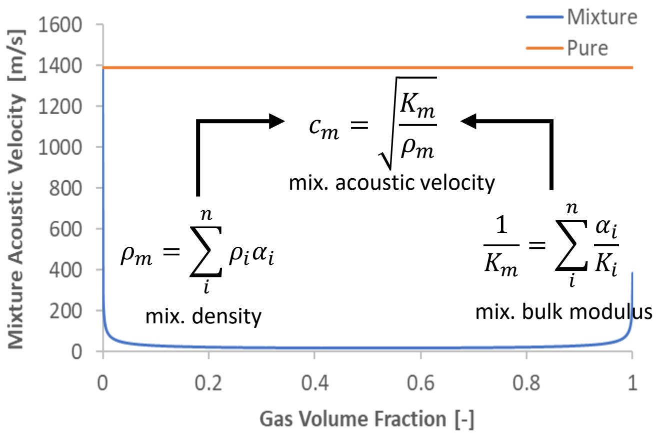
Acoustic waves traveling through the fluid to transmitters

Acoustic waves traveling from the rock back to the fluid and to the receiver



Sonic Logging: Illustration of acoustic logging with a source (transmitter) and an array of receivers. 9

Literature review and numerical analysis show promising results for early kick detection via **LWD and acoustic methods** Sonic signals are sensitive to variations of gas fraction bringing up the potential of using LWD and acoustic methods for early kick detection.



9) Wang et al. Bottomhole Acoustic Logging. https://doi.org/10.1007/978-3-030-51423-5

Computational Acoustic: Pressure Acoustics (Fluid)

Modeling Sound Wave propagation

General Scalar Wave Equation (GSWE): Simulation of custom acoustic propagation.

$$\frac{1}{\rho c^2}\frac{\partial^2 p_t}{\partial t^2} + \nabla \cdot \left(-\frac{1}{\rho}(\nabla p_t - \mathbf{q}_d)\right) = Q_m$$

- Describes small acoustic pressure variations (p_t)
- Accommodates monopole (Q_m) and dipole sources ($\mathbf{q}_d$)
- Flexibility to incorporate fluid-solid interactions -> different modes of propagation

Current simplifications/challenges:

- Resonance effects are neglected
- Interphase (mass/momentum) transfer is neglected

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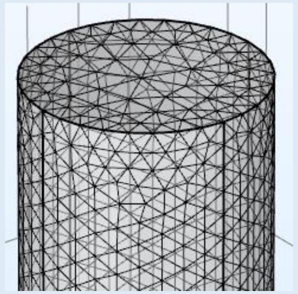
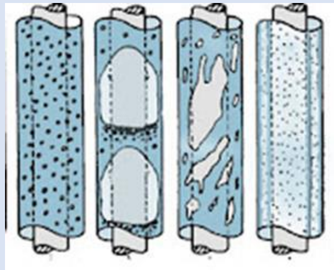
Modeling Two-Phase Medium:

Two-phase gas-liquid mixtures may be expected in the event of a gas kick

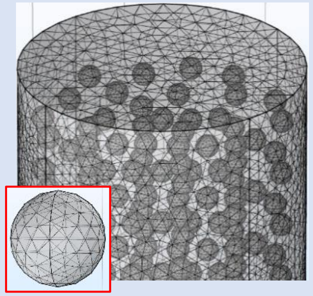
1) Homogenized model using a mixture approximation (Wood's Equation):

$$\frac{1}{c_{mix}^2} = (\alpha_g \rho_g + \alpha_l \rho_l)\left(\frac{\alpha_l}{\rho_l c_l^2} + \frac{\alpha_g}{\rho_g c_g^2}\right)$$





2) Discrete bubble approach



+ Does not require a mixture model
+ Allows for scattering
− Computationally expensive

Computational Acoustic: Pressure Acoustics (Fluid)

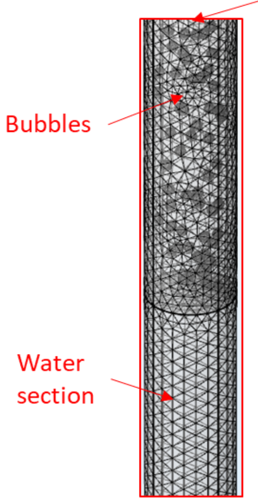
Wave Propagation in a Wellbore

Water and Multiphase Section (2% Void fraction)

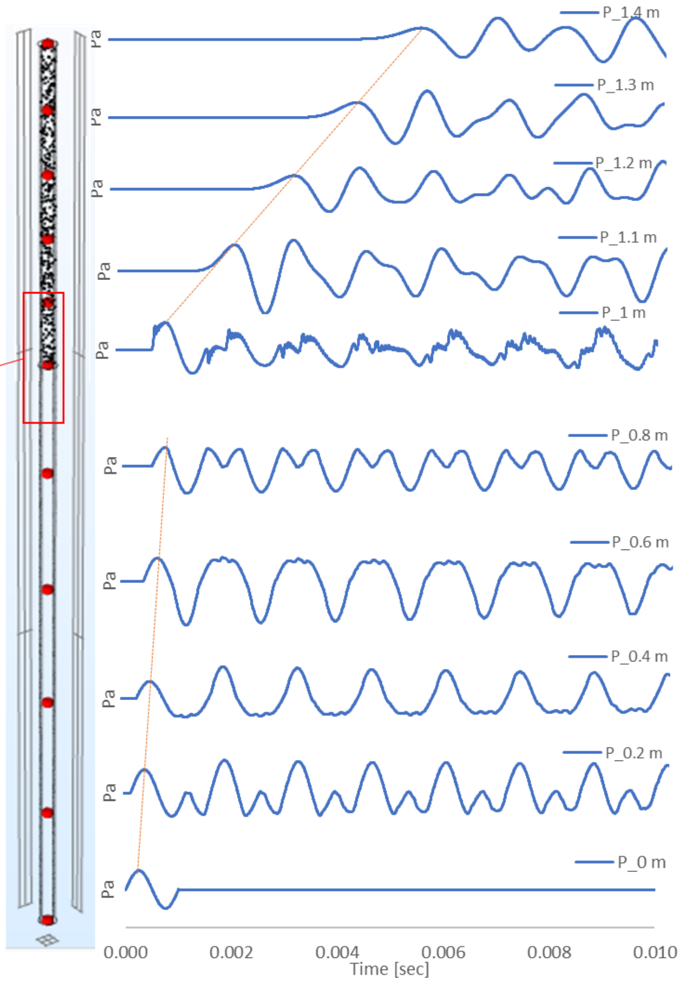
Pipe:
- **D_pipe** = 0.025 m
- H_pipe = 1 m

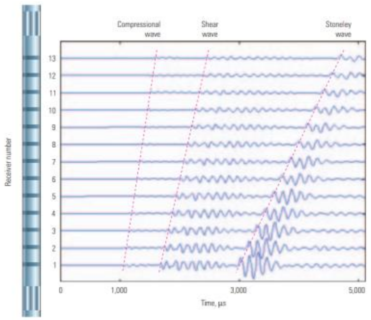
Random Bubbles
- D_bubble = 3 mm
- Void Fraction = 2 %

Signal:
- Frequency = 1 kHz
- Amplitude = 10 Pa

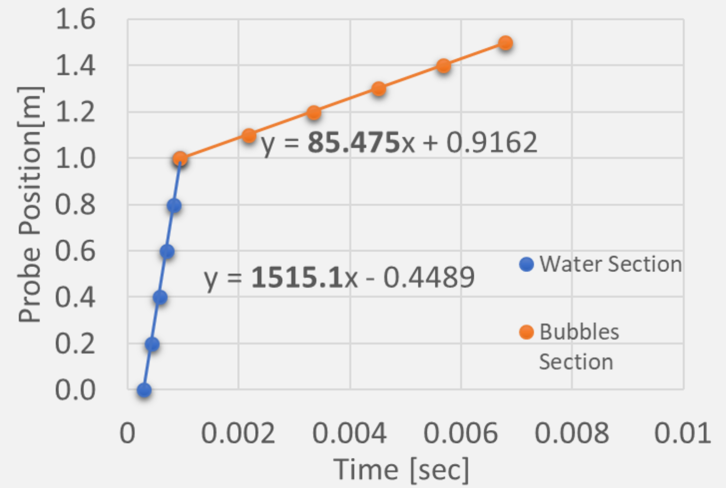


Grid Detail





Speed of sound analysis: First peak arrival at probes



Input data:

Gas fraction = 2 %

$c_{water} = 1480\ m/s$

$c_{air} = 343\ m/s$ (bubbles)

Signal freq = 1000 Hz

COMSOL Results:

$c_{water} = 1515.1\ m/s$

$c_{mix} = 85.47\ m/s$

Analytic for α = 2%

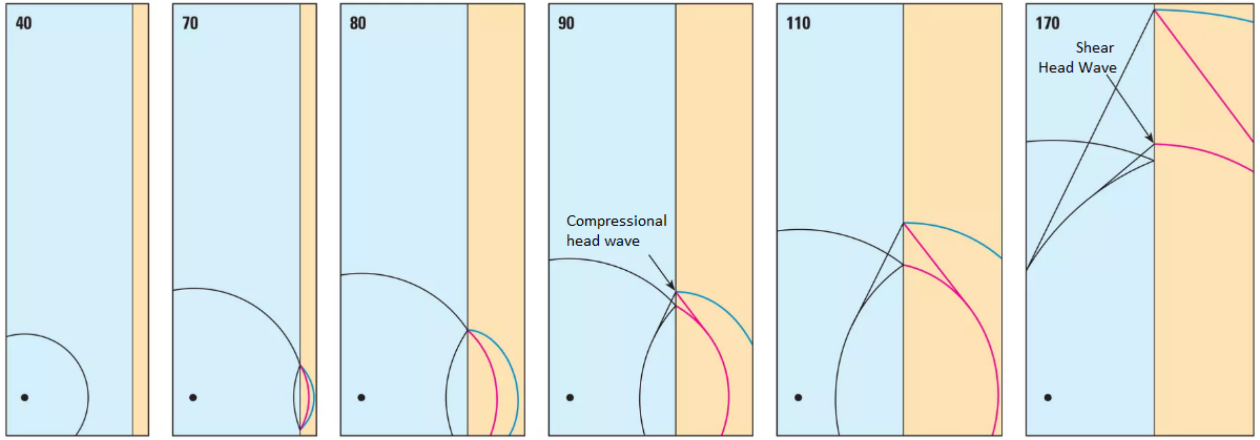
$c_{mix-Wood's} = 85.6\ m/s$

Error of c_{water} 2.4% and c_{mix} 0.15%

A similar speed of sound to the water and the effective mixture model is predicted

Computational Acoustic: Pressure Acoustics (Fluid)

Wave Propagation in Wellbore
Pressure acoustic model considering density and speed of sound like the rock formation and a wellbore fluid of around **0.15 % gas fraction**.
No solid mechanics modeling is involved.



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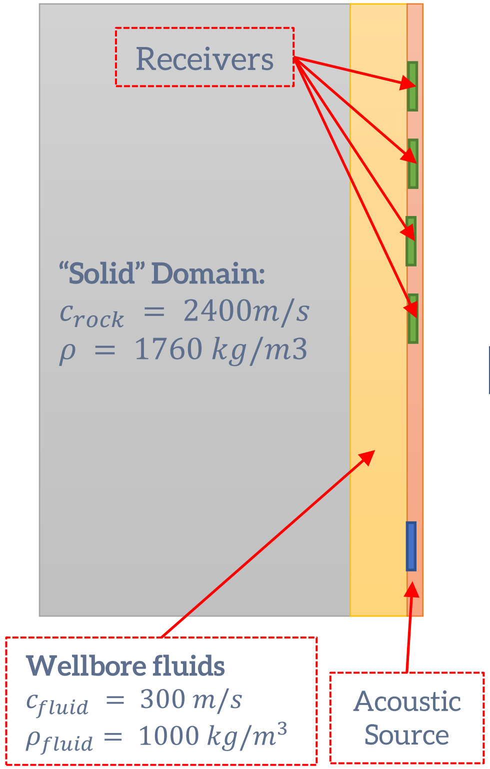
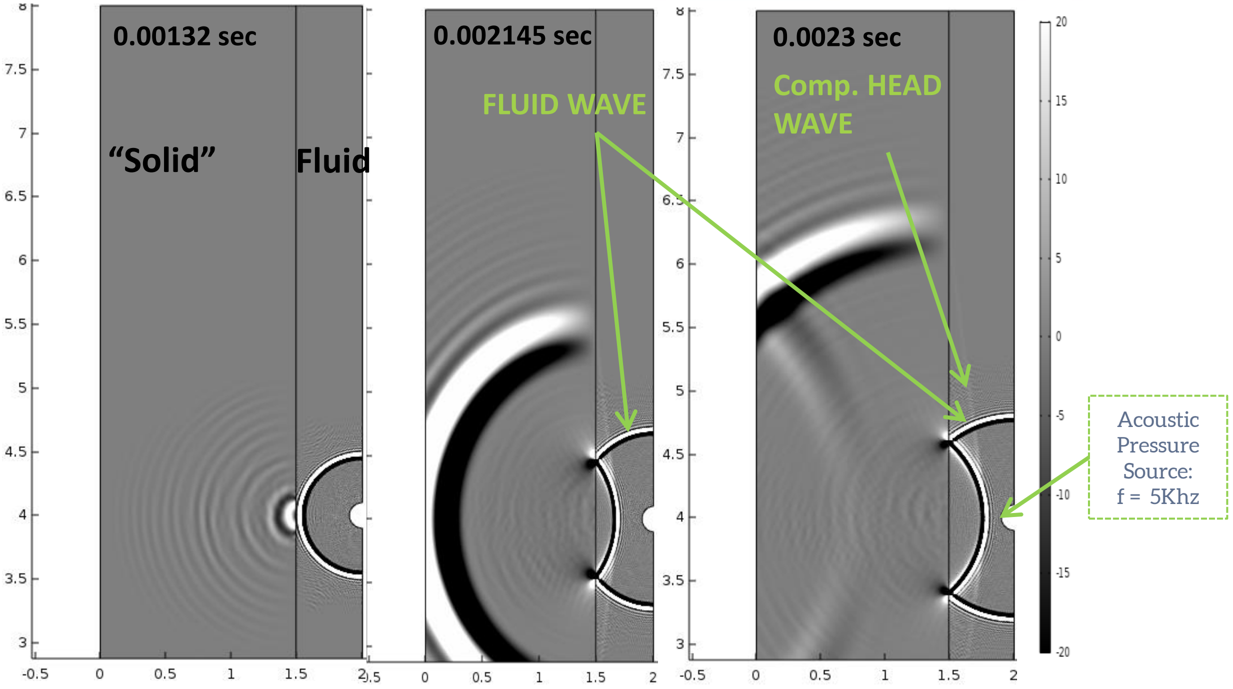
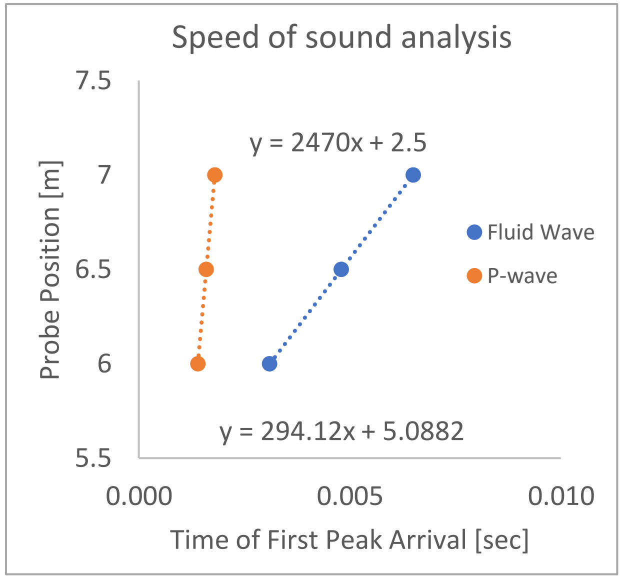




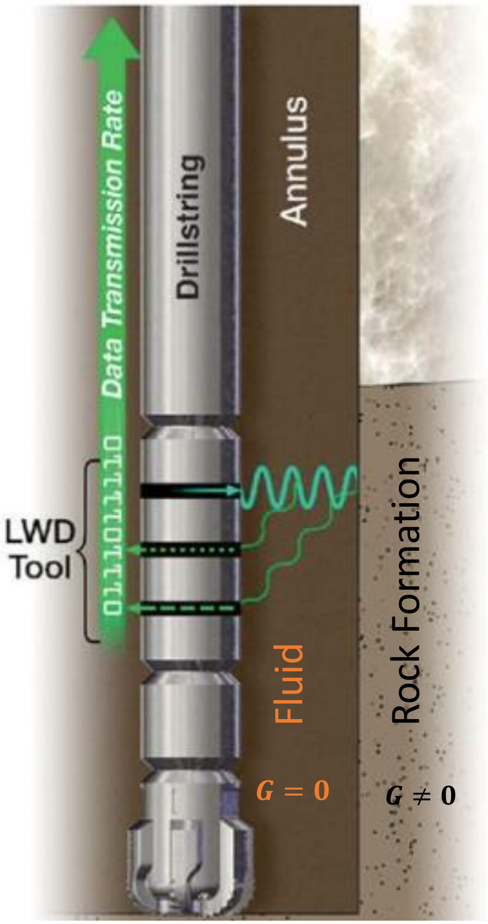


Computational Acoustics: Solid Mechanics (Solid)

Wave propagation in a through depends on solid mechanical Mechanical Properties

- Elastic waves in rocks propagate with a velocity that is given by elastic stiffnesses and the density (ρ) of the solid material. (Fjær et al, 2008)

- Speed of sound of compressional wave (c_P) and shear wave (c_S) are defined based on the mechanical properties



Speed of sound of compressional Wave (p-wave)

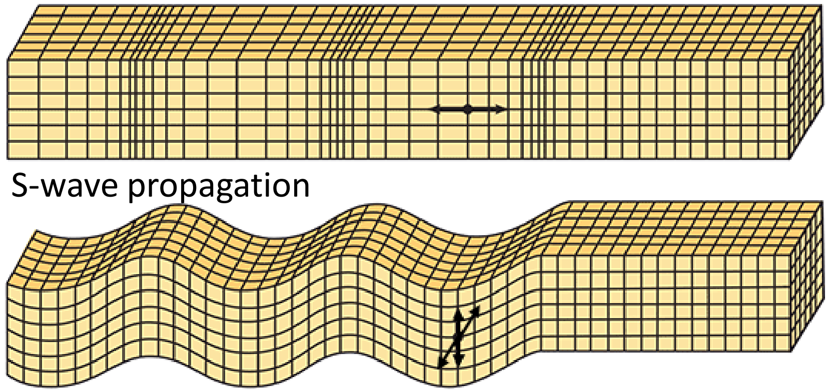
$$c_p = \sqrt{\left(K + \frac{4}{3G}\right)/\rho}$$

Speed of sound of Shear Wave (s-wave)

$$c_s = \sqrt{G/\rho}$$

G: Shear Modulus
K: Bulk Modulus
ρ: Density

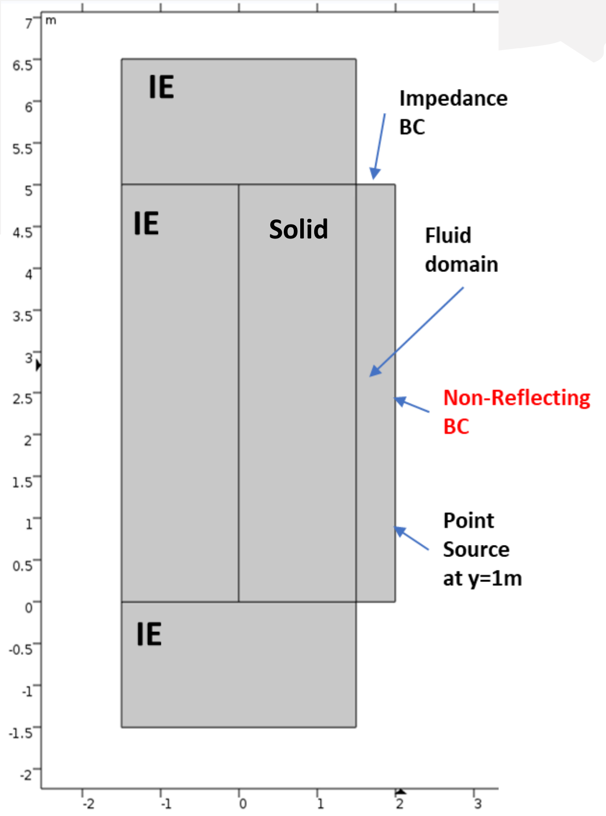
P-wave propagation [8]



S-wave propagation

8) Peterie, Shelby L., Richard D. Miller, and Julian Ivanov. "Seismology and its applications in kansas." *Kansas: Kansas Geological Survey* (2014).

Wave Propagation in Wellbore: Multiphysics



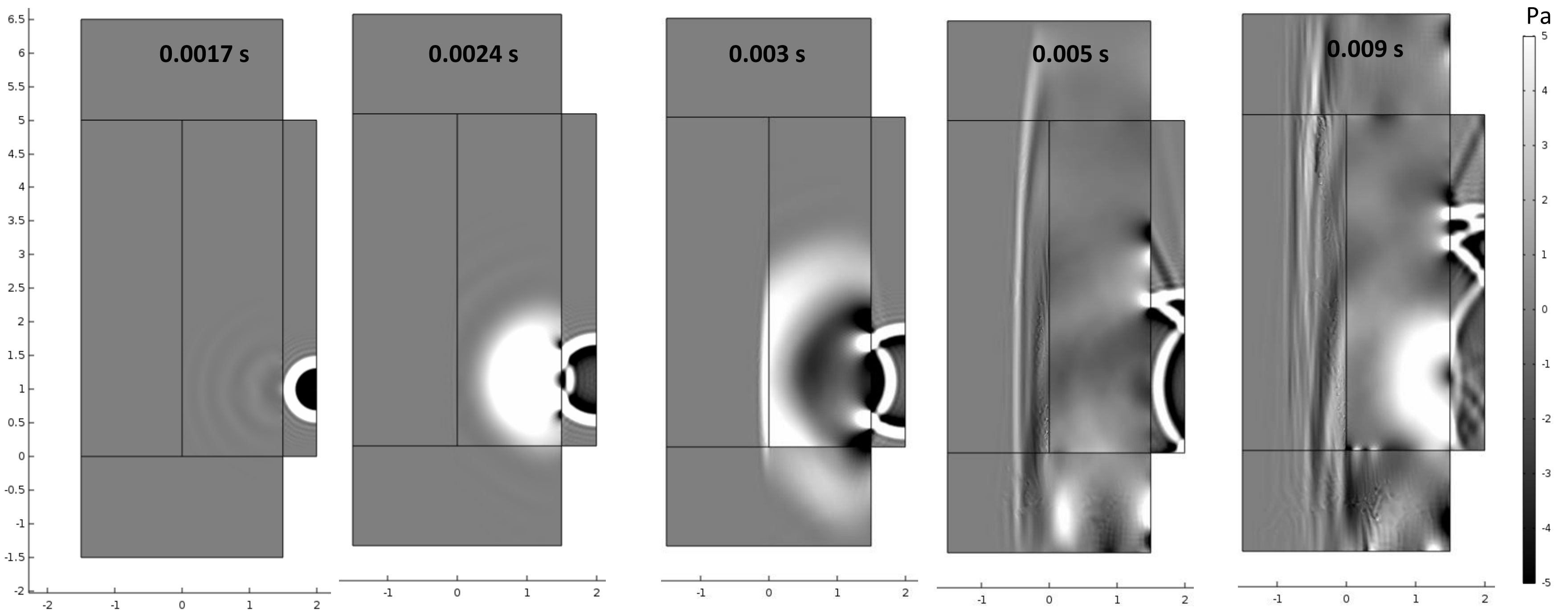
Fluid Domain
rho = 1000 kg/m3
c = 300 m/s
Lx = 0.5 m
Ly = 5 m

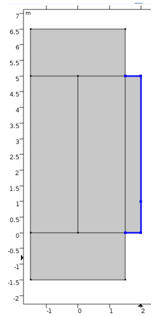
Rock
$rho = 1760\ kg/m3$
$c_{comp} = 1880\ m/s$
$c_{shear} = 767\ m/s$
Lx = 1.5 m
Ly = 5 m

(IE): Infinite element absorbing domain

Multiphysics: Pressure Acoustics + Solid Mechanics

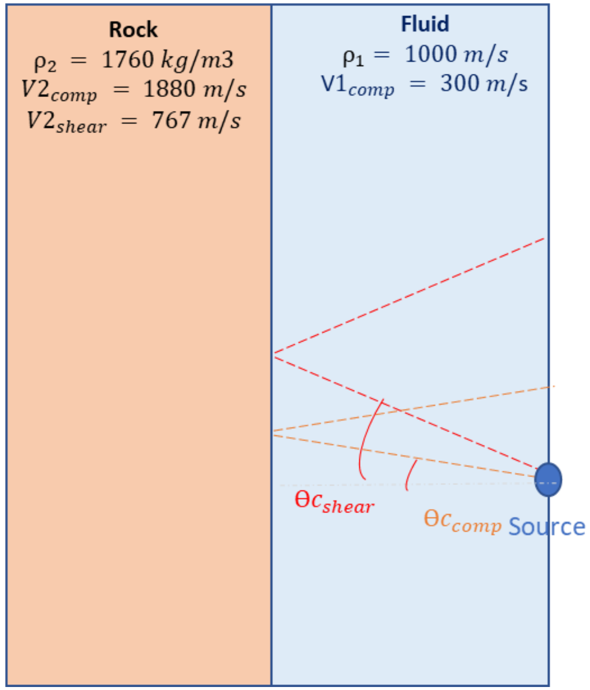
Transient evolution of acoustic wave propagation





Wave Propagation in Wellbore: Multiphysics

Critical angles (θc) validation: Compressional and shear waves

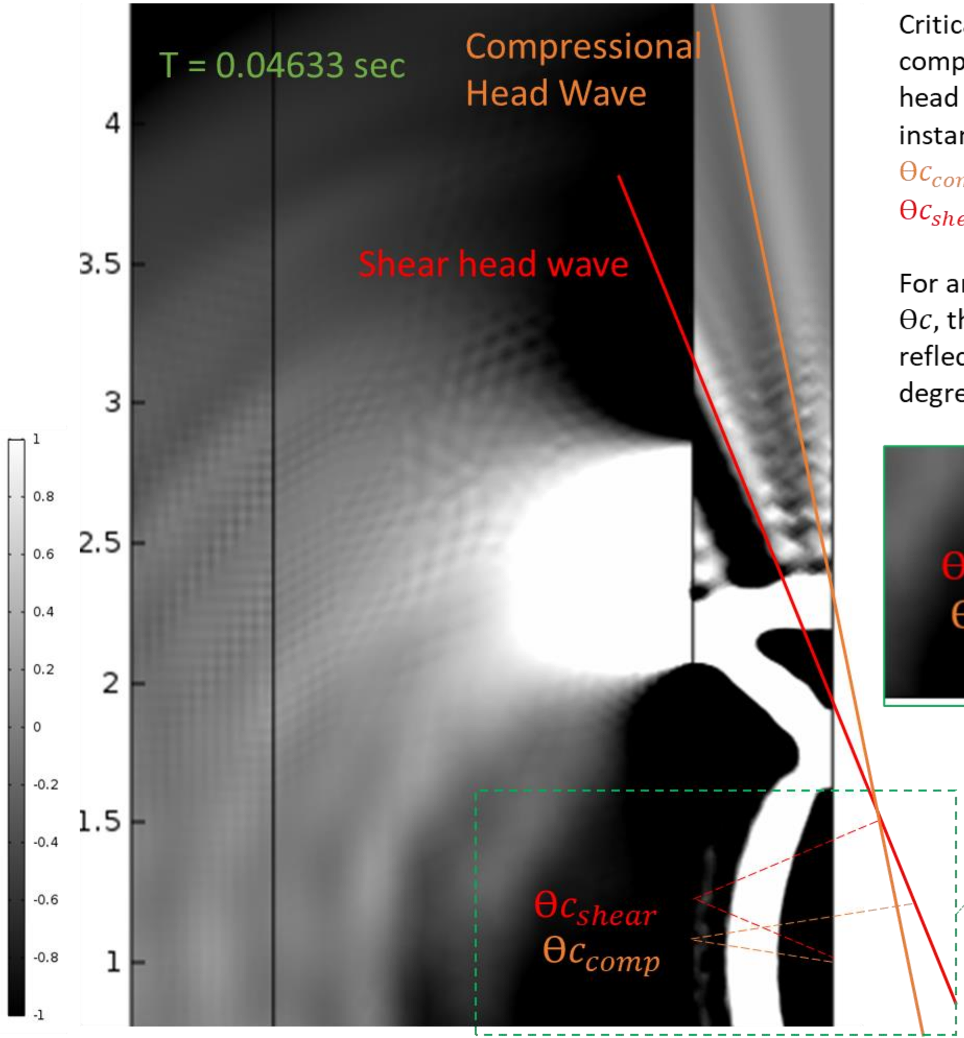


Compressional Wave

- $\theta c_{comp} = \arcsin(V1_{comp}/V2_{comp})$
- $\theta c_{comp} = \arcsin(300/1880)$
- $\theta c_{comp} = 9.18$

Shear Wave

- $\theta c_{shear} = \arcsin(V1_{comp}/V2_{shear})$
- $\theta c_{shear} = \arcsin(300/767)$
- $\theta c_{shear} = 23.02$

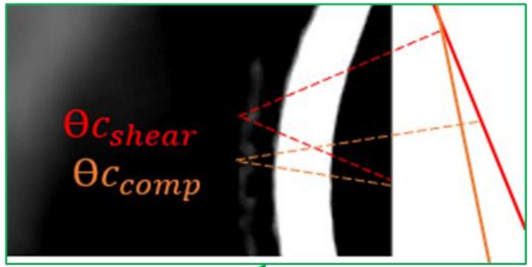


Critical Angles Representation compressional head waves and shear head waves are visible at this specific instant of time.

$\theta c_{comp} = 9.182$

$\theta c_{shear} = 23.02$

For angles of incidence larger than θc, the sound wave is completely reflected out or at least refracted to 90 degrees creating a surface wave.



**The model can accurately predict the critical angles for both p-wave and s-wave

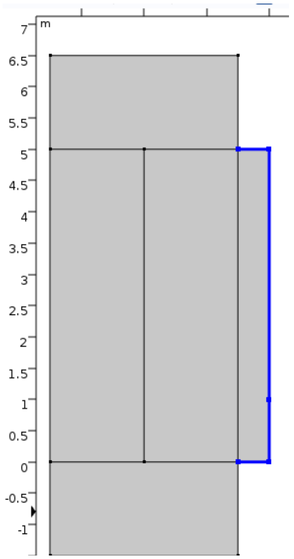
Wave Propagation in Wellbore: Multiphysics

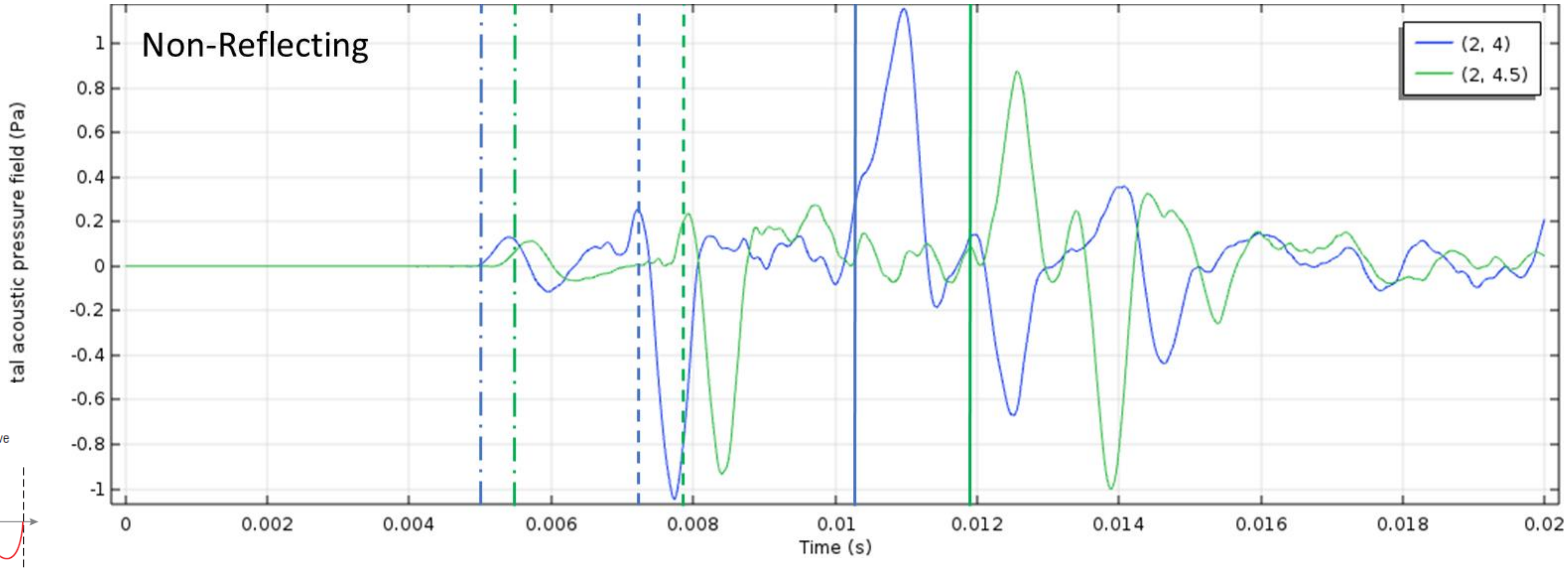
Wave Propagation in Wellbore

Head wave compressional
t_Hcomp (sec) = 0.005136 @4m
t_Hcomp (sec) = 0.0054 @4.5m

Shear Head wave
t_Hshear (sec) = 0.00723 @4m
t_Hshear (sec) = 0.00788 @4.5m

Direct Arrivals
t_Dm (sec) = 0.01025 @4m
t_Dm (sec) = 0.01192 @4.5m





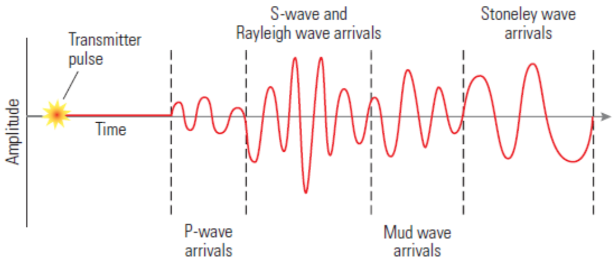
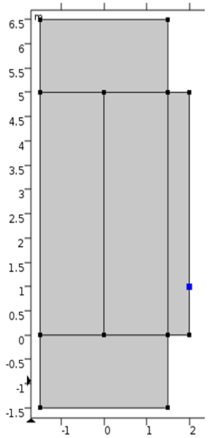
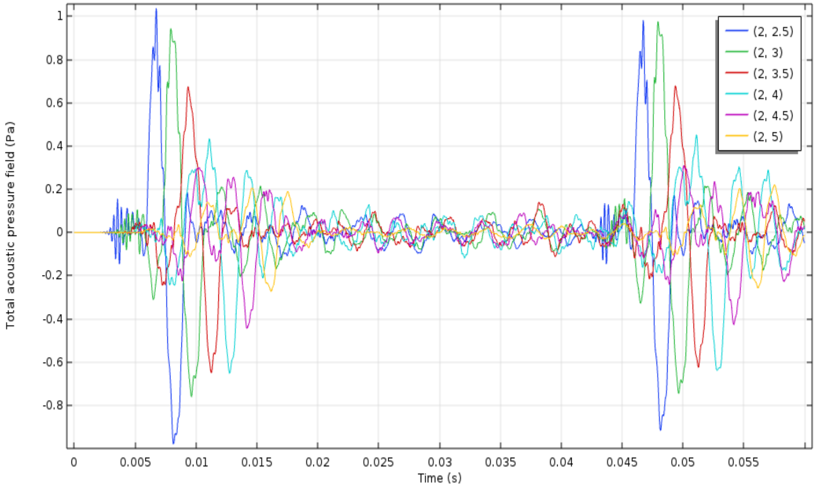


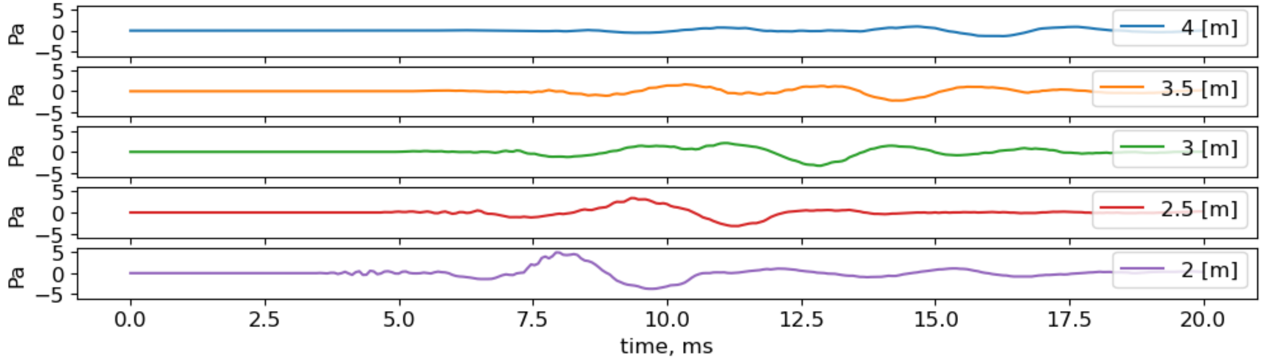
Image from[4]

4) Alford, et al., Oilfield Review Spring 2012: 24, no. 1.; 11) Haldorsen, et al., Oilfield Review, Borehole Acoustic Waves, Spring 2006.

Signal Analysis/Algorithm Development

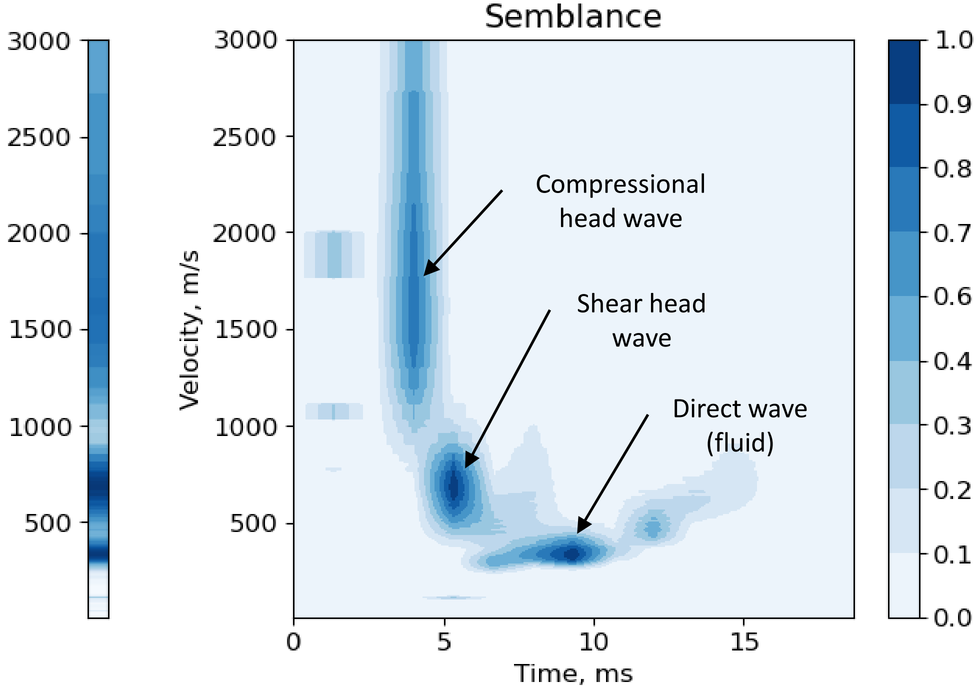






Simulation:
F0 = 300Hz
Monopole Source Amplitude = 10 Pa

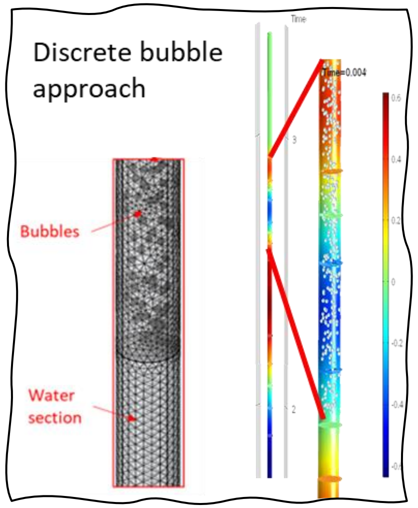
Compressional head wave: cp = 1880 m/s
Shear head wave: cs = 767 m/s
Direct mud wave: c_{fluid} = 300 m/s

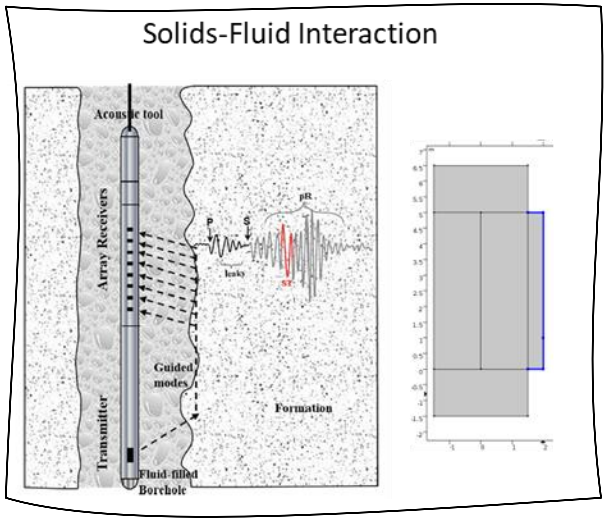


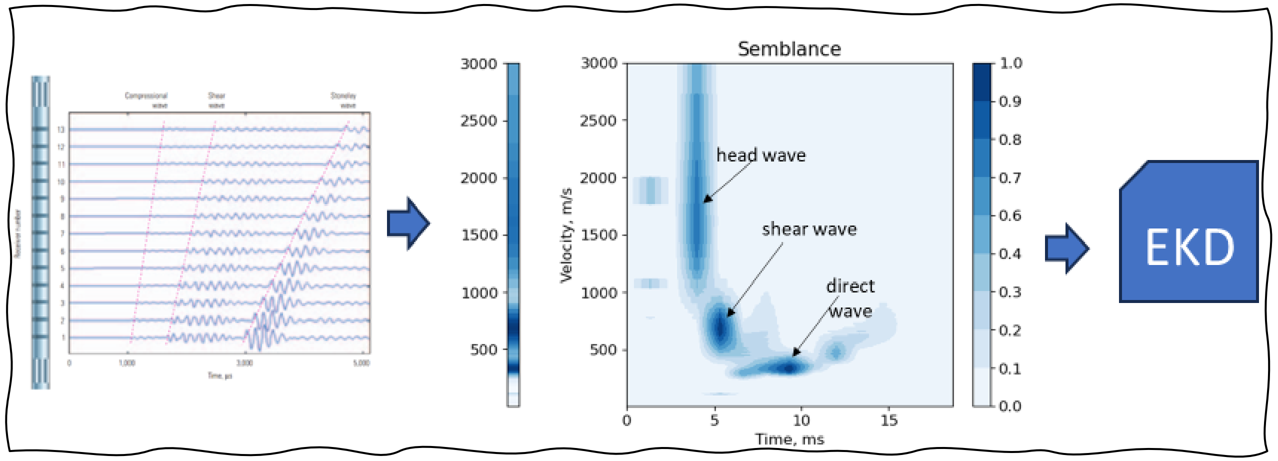
Semblance Plot:
Conventional methods to automate, visually, and identify the propagation modes.

Final Remarks / Next Steps

- The model can accurately predict the speed of sound of p-wave and s-wave
- Continue to Explore Solids-Fluid Interaction Component
    - Can we identify and use the stoneley wave to detect changes in the fluid gas fraction
- Discrete bubble approach
    - Investigate how the bubble mixture as opposed to homogenous mixture impacts wave train
- Automate data analysis method (identifying a kick)
    - Signal analysis/machine learning techniques
    - Can we identify a kick using the wave train?







Acknowledgements

- Louisiana State University
- National Energy Technology Laboratory
- Oregon State University

Questions?

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References

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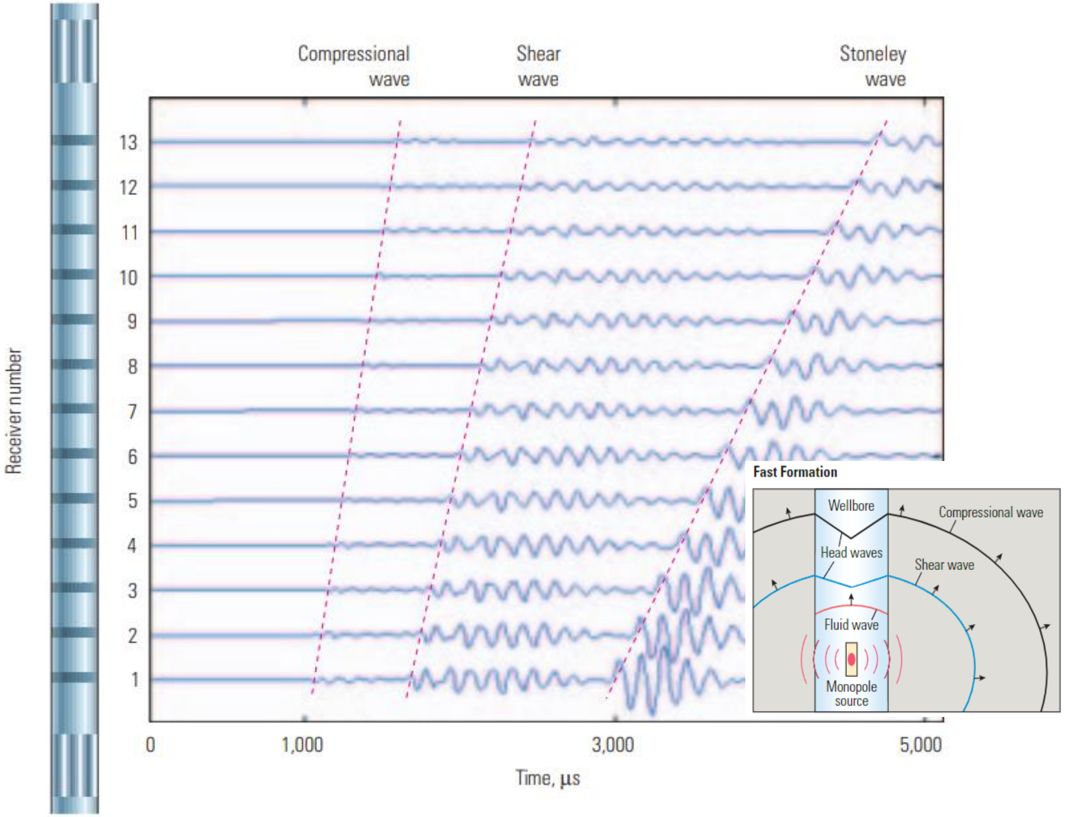
10) Haldorsen et al., Borehole Acoustics. Ridgefield, Connecticut, USA. 2006

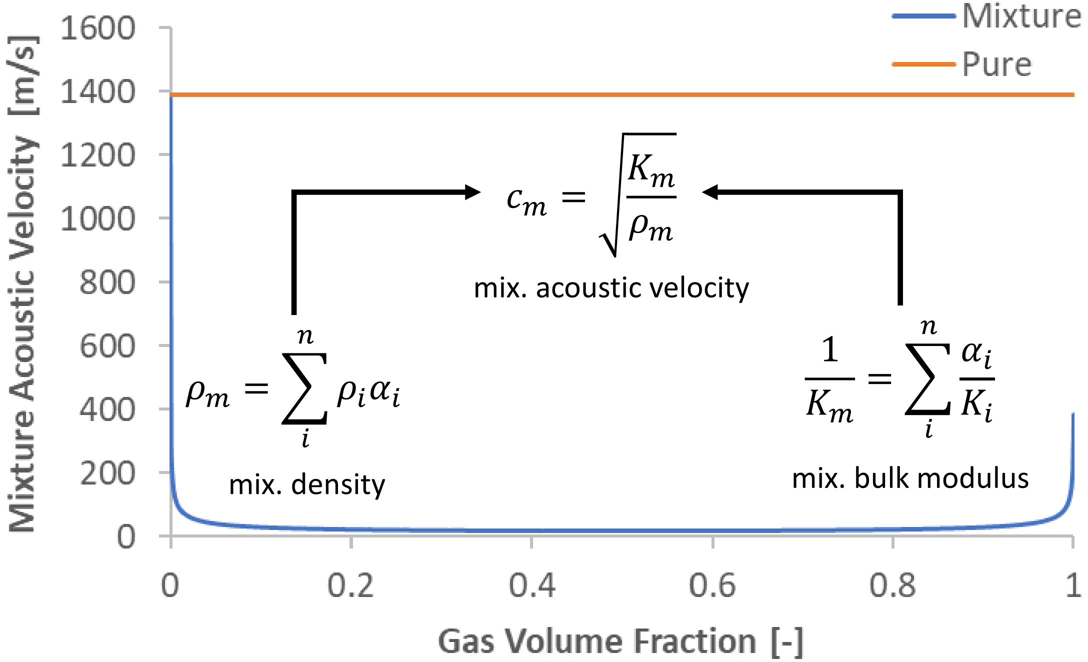
Backup Slides

Acoustic Velocity: Logging While Drilling



Typical waveforms from LWD signal in a fast formation showing compressional, shear, and Stoneley waves. (Haldirsen et al, 2006)

Literature review and numerical analysis show promising results for early kick detection via **LWD and acoustic methods**



Sonic signals are sensitive to variations of gas fraction bringing up the potential of using LWD and acoustic methods for early kick detection.

Computational Acoustic: Pressure Acoustics (Fluid)

- Modeling Sound Wave propagation: The General Scalar Wave Equation (GSWE) allows simulation of custom acoustic properties:

$$\frac{1}{\rho c^2}\frac{\partial^2 p_t}{\partial t^2} + \nabla \cdot \left(-\frac{1}{\rho}(\nabla p_t - \mathbf{q}_d)\right) = Q_m$$

- Describes small acoustic pressure variations (p_t)
- Accommodates monopole (Q_m) and dipole sources ($\mathbf{q}_d$)
- Flexibility to incorporate fluid-solid interactions -> different modes of propagation

In a gas kick event, two-phase mixtures are expected.

Wood's 1989 Equation: Mixture Speed of Sound

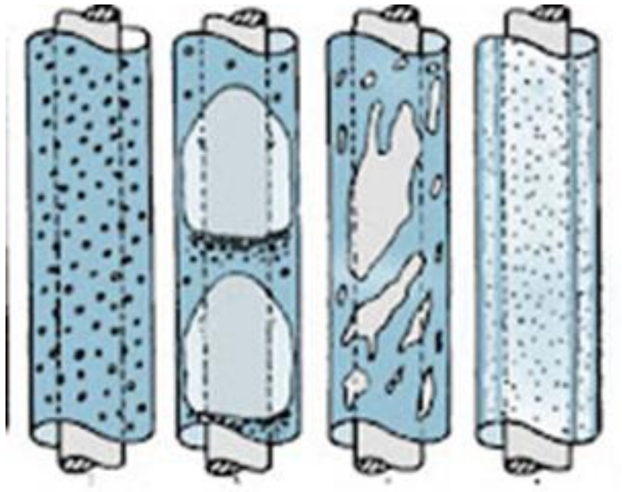
(l and g denote liquid and gas respectively)

$$\frac{1}{c_{mix}^2} = (\alpha_g \rho_g + \alpha_l \rho_l)\left(\frac{\alpha_l}{\rho_l c_l^2} + \frac{\alpha_g}{\rho_g c_g^2}\right)$$

Computational Acoustic: Pressure Acoustics (Fluid)

Modeling Two-Phase Medium:

Two-phase gas-liquid mixtures may be expected in the event of a gas kick

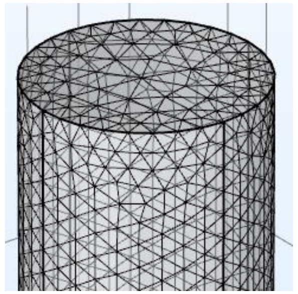


Current simplifications/challenges:

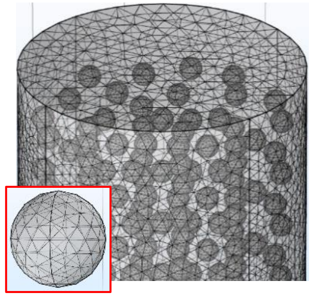
- Resonance effects are neglected
- Interphase (mass/momentum) transfer is neglected

- Homogenized model using a mixture approximation (Wood's Equation):

$$\frac{1}{c_{mix}^2} = (\alpha_g \rho_g + \alpha_l \rho_l)\left(\frac{\alpha_l}{\rho_l c_l^2} + \frac{\alpha_g}{\rho_g c_g^2}\right)$$

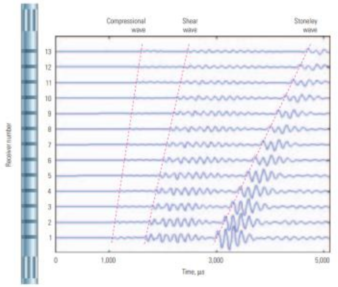


- Discrete bubble approach



+ Does not require a mixture model
+ Allows for scattering
– Computationally expensive

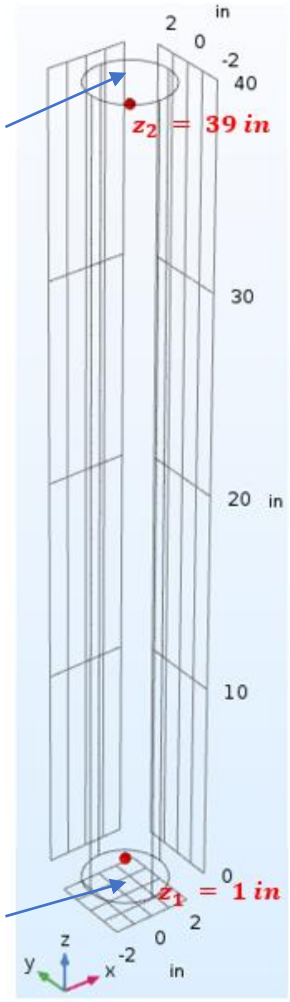
Speed of Sound (SoS) Determination



Non-reflecting BC

SoS of the medium
59.1 m/s

Pressure source

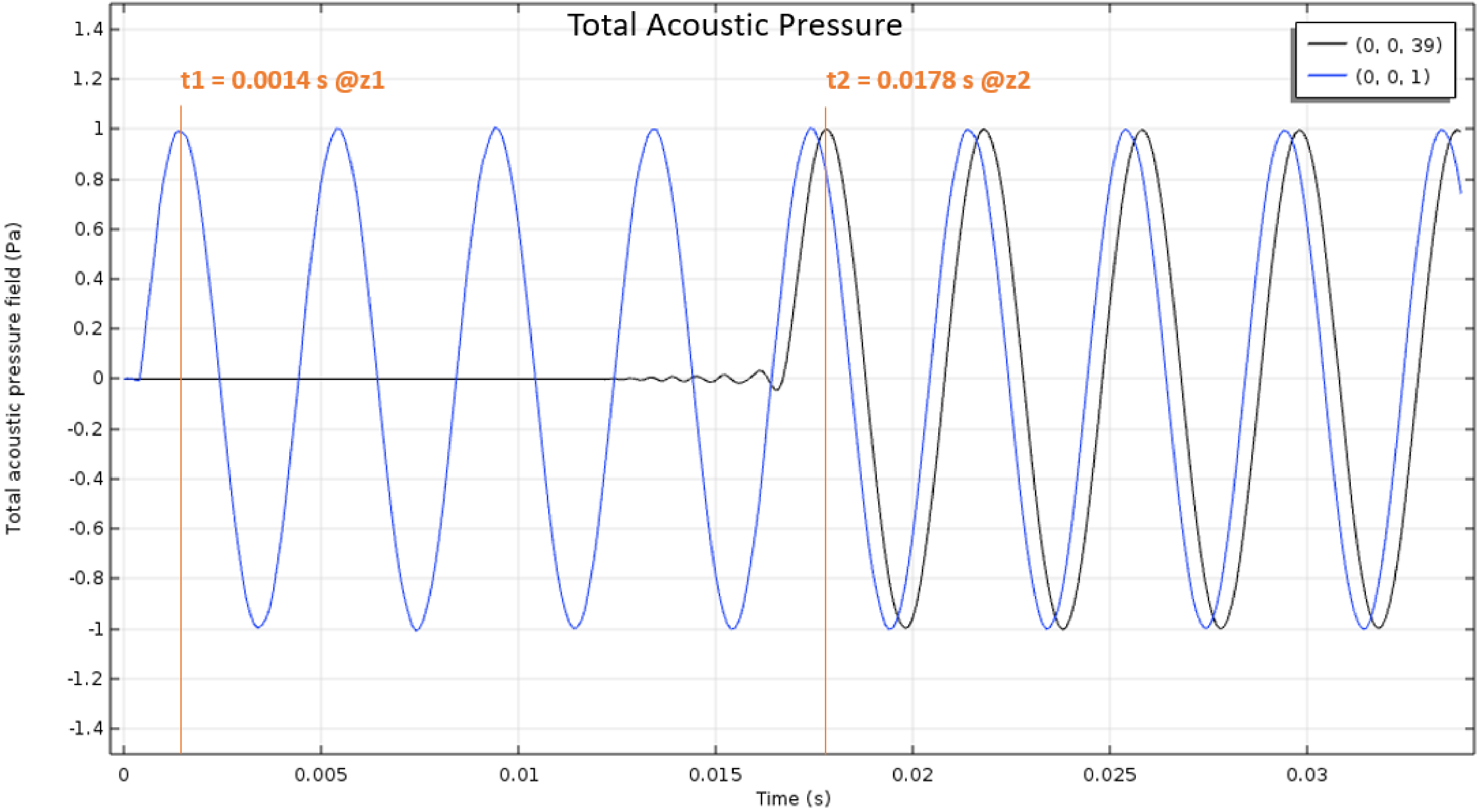


$z_2 - z_1 = 38\ in$

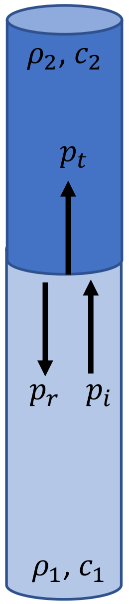
Calculated Speed of Sound (SoS) using signal arrival time at distinct probe locations

SoS = (39-1)[in]*0.02549[m/in]/(0.0178 – 0.0014)[s]

SoS = 59.06 m/s



Reflection & Transmission Validation

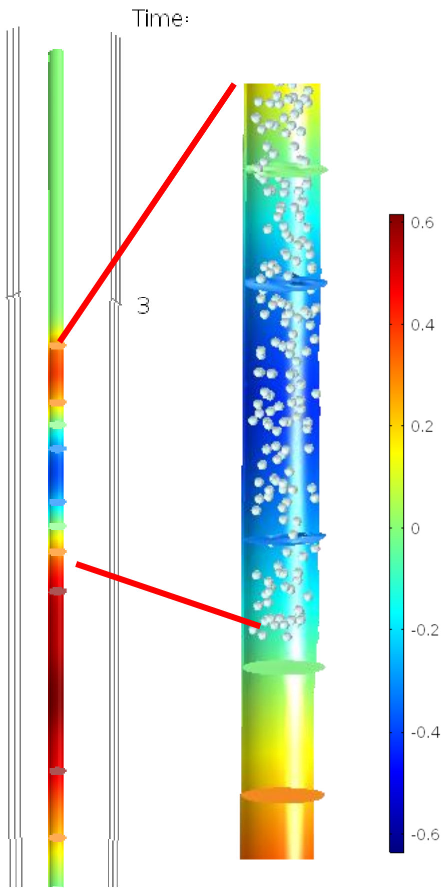


Analytic Model

$Z_i = \rho_i c_i$

$R_{12} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$

$T_{12} = 1 + R_{12} = \frac{2Z_2}{Z_2 + Z_1}$



Liquid into Mixture (bubbles)

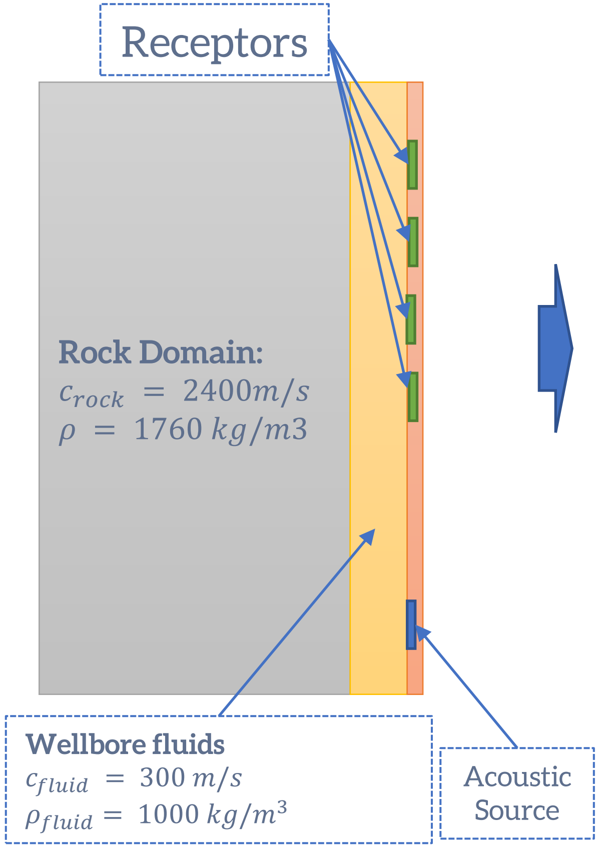
Impedance Ratio (Z_2/Z_1) 0.2369

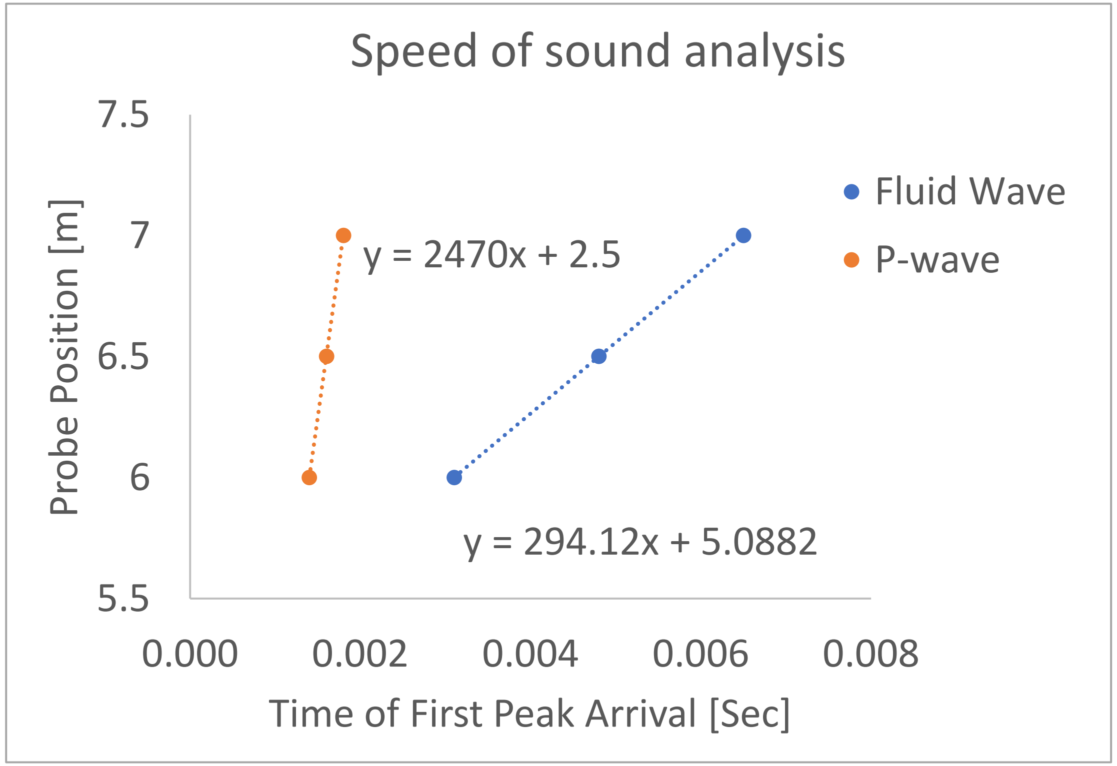
Approach	**Incident P_i (Pa)**	**Reflected P_r (Pa)**	**Transmitted P_t (Pa)**	**$(P_t-P_r)/P_i$**
Analytic Model	1	-0.61695	0.383050018	1
Sim. Homogeneous	1	-0.628	0.38	1.008
Sim. Discrete Bubble	1	-0.605	0.375	0.98

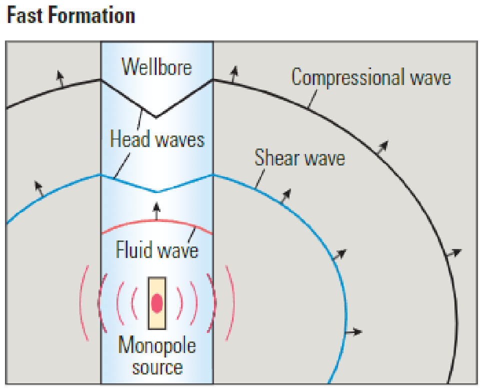
- **Similar *initial* incident reflected & transmitted pressure amplitudes are predicted**
- **Agree well with analytic theory**

Wave Propagation in Wellbore: Pressure Acoustics

This simulation consists of a pressure acoustic model considering properties of density and speed of sound similar to the rock formation and a wellbore fluid of around 0.15 % gas fraction. No solid mechanics modeling involved.







Wave Propagation in Wellbore: Multiphysics

Multiphysics: Pressure Acoustics + Solid Mechanics

Fluid Domain

rho = 1000 kg/m3

c = 300 m/s

Lx = 0.5 m

Ly = 5 m

Rock

rho = 1760 kg/m3

c_comp = 1880 m/s

c_shear = 767 m/s

Lx = 1.5 m

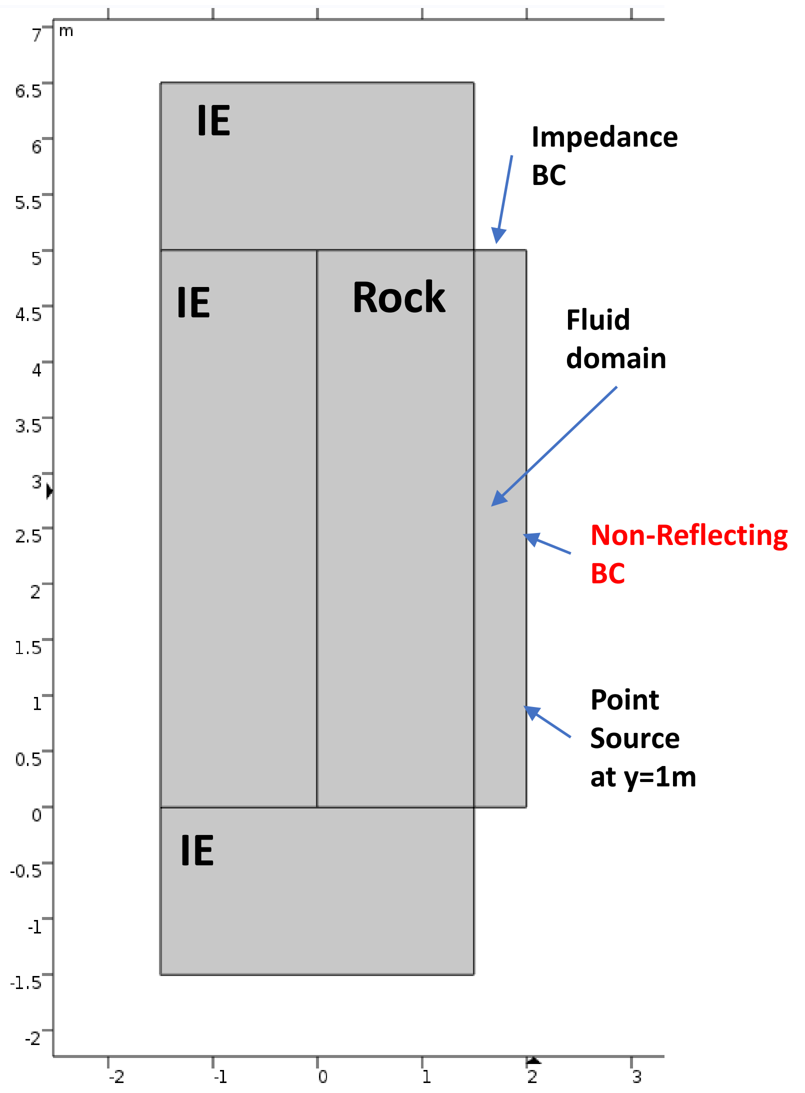
Ly = 5 m

Absorbing Domain with (Infinite Element)

- Rock properties
- rho = 1760 kg/m3
- c_ comp = 1880 m/s
- c_shear = 767 m/s
- IE thickness 1.5 m from solid border

Source:

- Monopole point source
- F0 = 1000[Hz]
- Single 10 Pa amplitude
- if(t<T0,A*sin(omega0*t),0)



Computational Acoustics: Solid Mechanics

- Elastic waves in rocks propagate with a velocity that is given by elastic stiffnesses and the density (ρ) of the solid material. (Fjær et al, 2008)
- Speed of sound of compressional wave (c_P) and shear wave (c_s) are defined based on the mechanical properties

$$c_p = \sqrt{\left(K + \frac{4}{3G}\right)/\rho}$$

Speed of sound of Shear Wave

$$c_s = \sqrt{G/\rho}$$

DESCRIPTION	VARIABLE	$D(E,\nu)$	$D(E,G)$	$D(K,G)$	$D(\lambda,\mu)$
Young's modulus	$E =$	E	E	$\frac{9KG}{3K+G}$	$\mu\frac{3\lambda+2\mu}{\lambda+\mu}$
Poisson's ratio	$\nu =$	ν	$\frac{E}{2G}-1$	$\frac{1}{2}\left(1-\frac{3G}{3K+G}\right)$	$\frac{\lambda}{2(\lambda+\mu)}$
Bulk modulus	$K =$	$\frac{E}{3(1-2\nu)}$	$\frac{EG}{3(3G-E)}$	K	$\lambda+\frac{2\mu}{3}$
Shear modulus	$G =$	$\frac{E}{2(1+\nu)}$	G	G	μ
Lamé parameter λ	$\lambda =$	$\frac{E\nu}{(1+\nu)(1-2\nu)}$	$\frac{G(E-2G)}{3G-E}$	$K-\frac{2G}{3}$	λ
Lamé parameter μ	$\mu =$	$\frac{E}{2(1+\nu)}$	G	G	μ
Pressure-wave speed	$c_p =$	$\sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}$	$\sqrt{\frac{G(4G-E)}{\rho(3G-E)}}$	$\sqrt{\frac{K+4G/3}{\rho}}$	$\sqrt{\frac{\lambda+2\mu}{\rho}}$
Shear-wave speed	$c_s =$	$\sqrt{\frac{E}{2\rho(1+\nu)}}$	$\sqrt{G/\rho}$	$\sqrt{G/\rho}$	$\sqrt{\mu/\rho}$

$$CC(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} a(t)b(t+\tau)dt$$

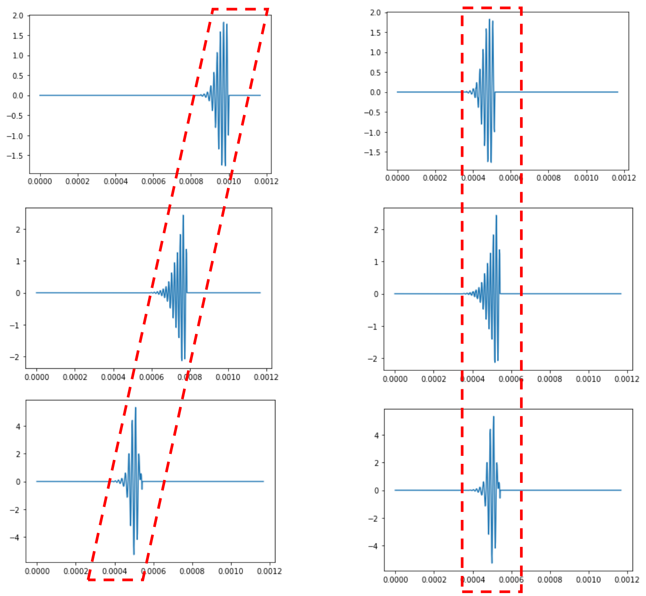
Cross Correlation

$$\rho^2(v,\tau) = \frac{\frac{1}{M}\int_{t=0}^{T_w} \left[\sum_{m=1}^{M} r_m\left[t+\left(\frac{z_m}{v}\right)+\tau\right]\right]^2 dt}{\sum_{m=1}^{M}\int_{t=0}^{T_w} \left\{r_m\left[t+\left(\frac{z_m}{v}\right)+\tau\right]\right\}^2 dt}$$

Semblance

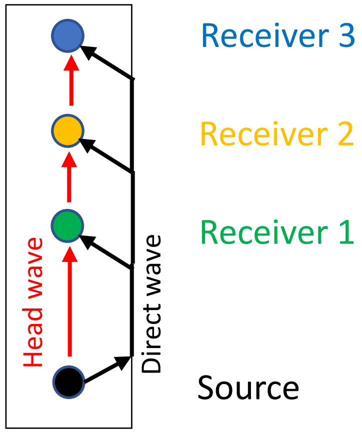
v: wave velocity, m/s
τ: time delay compared to the first wave arrival (m=1), s
M: number of receivers
T_w: time window, s
r_m(t): wave form recorded by receiver m
z_m: distance of receiver m from the first receiver, m

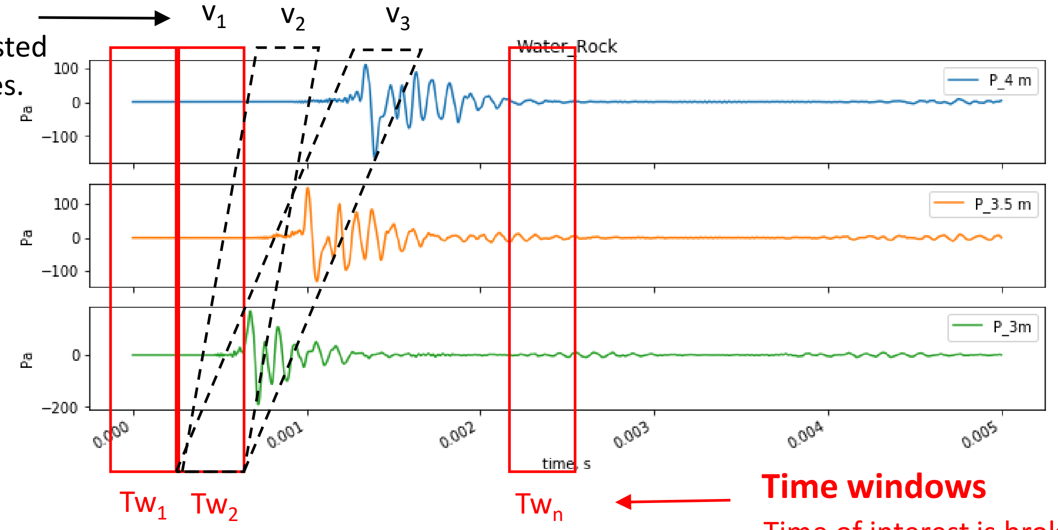
At each velocity, move-out correction is applied on the waveforms within the time window



Wave velocities

Each time window is tested with a range of velocities.





Time windows

Time of interest is broken into several time windows.