Stress dependent dynamic anisotropy in shales

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SINTEF Petroleum Research

The 9th Euroconference on Rock Physics and Geomechanics
October 20th, 2011, Trondheim
Introduction

• Rocks typically exhibit elastic anisotropic behaviour:
  – Intrinsic anisotropy (layering, grain orientation etc.)
  – Induced anisotropy (stress)
• Layered materials, like shales, are often assumed to have an isotropic behaviour in the bedding plane (Transverse Isotropy)
• Elastic properties of the rock is closely linked to wave velocities
• Importance
  – Seismic interpretation (exploration and time-lapse) and modelling
  – Borehole sonic logging
Introduction

• Measurement of the dynamic properties on a cylindrical core with TI properties requires 5 independent measurements

\[
\begin{pmatrix}
\sigma_x \\
\sigma_y \\
\sigma_z \\
\tau_{yz} \\
\tau_{xz} \\
\tau_{xy}
\end{pmatrix} =
\begin{pmatrix}
C_{11} & C_{11} - 2C_{66} & C_{13} & 0 & 0 & 0 \\
C_{11} - 2C_{66} & C_{11} & C_{13} & 0 & 0 & 0 \\
C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\
0 & 0 & 0 & C_{44} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & C_{66}
\end{pmatrix}
\begin{pmatrix}
\varepsilon_x \\
\varepsilon_y \\
\varepsilon_z \\
2\Gamma_{yz} \\
2\Gamma_{xz} \\
2\Gamma_{xy}
\end{pmatrix}
\]

• The TI anisotropy can be described by the Thomsen parameters:

\[
\varepsilon \equiv \frac{C_{11} - C_{33}}{2C_{33}}
\]

\[
\gamma \equiv \frac{C_{66} - C_{44}}{2C_{44}}
\]

\[
\delta \equiv \frac{1}{2C_{33}^2} \left[ 2\left( C_{13} + C_{44} \right)^2 - \left( C_{33} - C_{44} \right) \left( C_{11} + C_{33} - 2C_{44} \right) \right]
\]

Thomsen, 1986
Introduction

• Assumptions
  – Transverse Isotropy
  – Homogeneous
  – Cylinder axis is parallel to the bedding plane normal

• The elastic (dynamic) moduli:

\[
 C_{11} = \rho V_{p,\text{horizontal}}^2 \\
 C_{33} = \rho V_{p,\text{axial}}^2 \\
 C_{44} = \rho V_{s,\text{vertical\,(hor.)}}^2 \\
 C_{66} = \rho V_{s,\text{horizontal\,(hor.)}}^2 \\
 C_{13} = ?
\]

• Estimate \( C_{13} \) from Thomsen theory and oblique measurements of P-wave velocities
P-wave measurements

• Setup of 8 P-wave transducers:
  – Measurements in both principal directions
  – Four measurements in oblique directions

• Sleeve transducer specifications:
  – 3.5 mm outside diameter
  – Curved front
  – 1.3 MHz resonant frequency
  – Crystal diameter 2 mm

• P-wave velocities at the following inclinations: 0° (vertical), 18°, 37°, 47, 69° and 90° (horizontal)
Validation

• Group or phase velocities for oblique waves?
  – FD simulations
  – Synthetic materials
    • measurements at ambient conditions
    • measurement under stress on cylindrical samples
FD model

- Model with realistic geometries:
  - Transducers in the sleeve
    - 3.5 mm diameter
    - The source is simulated as a disk with 2 mm diameter and 0.075 mm thickness
    - ~0.4 mm titanium front piece
  - Oblique transducers in the piston
    - The source is a disk with 3.5 mm diameter and 0.075 mm thickness
    - ~0.4 mm steel front piece
- Spatial resolution is 0.075 mm
- Source signal is a Ricker wavelet with centre frequency of 1 MHz.
FD model simulations

• Material with TI properties:
  – Non-spherical wavefront
  – Wavefront normal oblique to transducer normal

Cross section of density model
Simulation results

- Velocities picked from wavefront arrival for two materials:
  - Weak TI ($\varepsilon=0.14$, $\delta=0.04$, $\gamma=0.28$)
  - Strong TI ($\varepsilon=0.3$, $\delta=0.3$, $\gamma=0.07$)

- Both simulations showed that the picked velocities fall on the line for the theoretical group velocity for the material.

10-20 m/s uncertainty in velocities
0-2 degrees uncertainty in angle
Materials

• Peek (used for calibration)
  – Isotropic
  – $V_P = 2564 \text{ m/s}$
  – $V_S = 1129 \text{ m/s}$
  – Density = $1.305 \text{ g/cm}^3$

• Bakelite (strong TI)
  – Anisotropic (quasi-TI)

• Pierre shale (weak TI)
  – Anisotropic (quasi-TI)
Bench setup for radial P wave measurements

- Sample characterization prior to triaxial testing
- Measurements done on both vertical and horizontal samples
Strong TI material

- Bakelite Cotton Phenolic (Etronax MF)
  - Density of 1371 kg/m³
  - VP (axial) = 2843 m/s
  - VS (axial) = 1533 m/s
  - Layered media
  - Weak anisotropy observed in horizontal plane
  - Homogeneous sample (repeatable measurements)
  - Measurement along the fastest horizontal plane direction gives:
    - Thomsen $\varepsilon = 0.30$
    - Thomsen $\delta = 0.30$
    - Thomsen $\gamma \approx 0.075$ (not perfect TI-media)
Weak TI material

- Pierre shale
  - Density of 2360 kg/m³
  - VP (axial) = 2325 m/s
  - VS (axial) = 878 m/s
  - Layered media
  - Weak anisotropy observed in horizontal plane
  - Homogeneous sample (repeatable measurements)
  - Measurement along the fastest horizontal plane direction gives:
    - Thomsen $\varepsilon = 0.14$
    - Thomsen $\delta = 0.04$
    - Thomsen $\gamma \approx 0.28$ (not perfect TI-media)
Bakelite triaxial experiment

- Hydrostatic cycling of cylindrical sample with bedding plane normal parallel to cylinder axis
- Measure five P-wave velocities
  - Vertical and horizontal
  - Three oblique directions
Bakelite triaxial experiment

- Oblique velocities fits well with theoretical line for group velocities
- Lower $\delta$ in triaxial setup than measured at ambient conditions
- No change in $\varepsilon$ nor $\delta$ when increasing hydrostatic pressure
Pierre shale triaxial experiment

- Hydrostatic cycling of cylindrical sample
- Uniaxial undrained loading
- Measure five P-wave velocities
  - Vertical and horizontal
  - Three oblique directions
Pierre shale triaxial experiment

- Bedding plane normal was found to be slightly off cylinder axis (~10 degrees).
- Oblique velocities fits well with theoretical line for group velocities.
- Higher $\delta$ in triaxial setup than measured at ambient conditions.
- Increase in $\delta$ when increasing mean stress (small shear stress).

\[ \varepsilon = 0.14 \]
\[ \delta = 0.14 \]

\[ \varepsilon = 0.16 \]
\[ \delta = 0.18 \]
Summary

- An ultrasonic experimental setup has been developed which allows for measuring 4 oblique P-wave velocities in a triaxial setup.
- FD simulations show that these velocities correspond to group velocities.
- Triaxial experiments were performed to verify the setup.
- Stress dependency of the Thomsen parameters $\varepsilon$ and $\delta$ on Pierre shale.
Acknowledgements

• The Shale Rock Physics Consortium is funded by BP, ConocoPhillips, Det Norske, DONG Energy, Shell and Total