Numerical Investigation of Surface Wave Anisotropy for Fault Characterisation in Geothermal Fields

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Aim:

Observe interaction of synthetic Rayleigh waves with subsurface faults.
Outline

• Why?
  • Outline the purpose of this presentation.

• Numerical Modelling
  • Background on the model used for generating surface waves.

• Rayleigh Wave Propagation
  • Examples of synthetic Rayleigh waves.

• 3C Beamforming
  • How we know it is Rayleigh waves and velocity analysis.

• Interpretations so far…

• What’s next?

• Overall summary
Why?

- Faults are fundamental in geothermal fields. Why? -> hydrothermal flow
- Rayleigh waves have been shown to interact with (sub) vertical faults at depth.

Problems:

- This is based on Rayleigh wave velocity variation assumptions when interacting with faults.

Figure 1: Fast directions and magnitude of apparent anisotropy of (a) Retrograde Rayleigh waves and (b) Love waves at varying depths, in the Los Humeros Geothermal Field Mexico. (Kennedy et al., 2022)
Numerical Modelling
Outline of Methodology

1 Slice (0.2 km y-direction) of 3D Model with a "water"-filled fault of 56 m width

- Vs of layer = 1500 ms\(^{-1}\)
- Vs of fault = 0 ms\(^{-1}\)
- 100 x 200 x 200 grid
- \(\lambda_{\text{max}} = 250\) m
- \(f_c = 6\) Hz

Simulation criteria:
- Stability: \(V_{\text{max}} \times \frac{\Delta t}{\Delta x} \leq 0.8\)
- Dispersion: \(\lambda_{\text{max}} = \frac{v_{\text{min}}}{f_{\text{max}}} \geq 10 \times \Delta x\)

Wave Response

Receiver Station Layout

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Rayleigh Wave Propagation
Rayleigh Wave Propagation

Homogeneous model
Homogeneous model
Rayleigh Wave Propagation

Heterogeneous model

Snapshot of Z-component of Displacement Wavefield

X direction

Depth (km) / Z direction

West East

Y direction

North South

Source A

“Water”-filled Fault

Receiver

Seismic2023 20th April 2023
Rayleigh Wave Propagation

Heterogeneous model

- Receiver
- Source B
- "Water"-filled Fault
Typically Retrograde Rayleigh (outlined box) waves are shown at the surface.

Prograde Rayleigh waves only tend to form due to a geologic change (e.g. sedimentary layer or fault) which reverses the particle motion.

Figure 2: A retrograde Rayleigh wave propagating in the x-direction. a) xsnap and b) zsnap. If you combine both of these, you get the particle motion of the wave (in orange).
3C Beamforming
Three-component synthetic noise data

**Input**

One time window

**3C Beamforming**

_after Riahi et al. (2013)_

\[
v(\theta) = a_0 + a_1 \cos(2\theta) + a_2 \sin(2\theta) + a_3 \cos(4\theta) + a_4 \sin(4\theta)
\]

One frequency, one time window

**Wave characteristics**

*Beam power*

*Polarization*

**Output: Anisotropy Analysis**

Anisotropy _Curve_

-Kennedy et al., 2022-
Interpretation so far...
One time window, one frequency

The velocity of maximum normalised energy
Retrograde Rayleigh wave
= 1.684 kms⁻¹

The velocity of maximum normalised energy
Retrograde Rayleigh wave
= 1.333 kms⁻¹
One time window, one frequency

The number of time windows (out of 15) Rayleigh waves were found.

<table>
<thead>
<tr>
<th></th>
<th>Source A</th>
<th>Source B</th>
</tr>
</thead>
<tbody>
<tr>
<td>No fault</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>Fault</td>
<td>6</td>
<td>8</td>
</tr>
</tbody>
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(above is based on Rayleigh waves corresponding to maximum normalised response energy)

- Fault created Rayleigh waves, but it was not the only cause.
- Rayleigh wave particle motion direction changed with the presence of the fault.
What’s next?
• Further synthetic wave type analysis for all wave arrival times/azimuth.
• Creating a synthetic anisotropy curve similar to real data below.

• Continuing this for faults of different geological situations.
Overall summary:

• Numerical modelling can be used to generate Rayleigh waves.
• Rayleigh waves travel faster when travelling along the “water-filled” fault.
• 3C beamforming can help depict wave types, propagation velocity and direction.

Any questions?
Further reading/future talks:


- EGC 1 Aberdeen: Day 3-Fault and Fracture Characterisation for the Energy Transition, https://www.energygeoscienceconf.org/technical-programme/
References:


• **RSD FD Scheme:**

(a) Standard Staggered Grid  
(b) Rotated Staggered Grid  
Saenger et al. (2000)

- gridpoints \( \rho \) : density  
- \( \lambda, \mu \) : Lamé parameters  
- staggered gridpoints \( u_z, u_x \) : displacement  
- \( \varepsilon_{ik} \) : strain

• **Stability and dispersion criteria:**

In place to create stability in the model (due to amplitude increasing exponentially with every timestep). Numerical dispersion (frequency-dependent velocity-based errors) is also an issue.