Pitfall in AVO Anisotropic Modeling: Plane Wave vs Spherical Wave

Qing Li
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A client uses the following model to model anisotropic AVO effects and raised the question of discrepancy between the results of Zoeppritz and Elastic Wave method.
Synthetics generated from the client’s model with Zoeppritz and Elastic Wave methods. (The event tilts up on far offset in few_aniso is due to over correction of NMO).
The amplitudes picked from the modeling results show an opposite response to anisotropy between Zoeppritz and Elastic Wave methods.

This discrepancy inspired the following study between the two methods. To make things simple, the following study uses a two layer Blangy model to study the causes of the discrepancy.
Blangy’s Model

<table>
<thead>
<tr>
<th>Materials</th>
<th>Vp (m/s)</th>
<th>Vs (m/s)</th>
<th>Density</th>
<th>Delta</th>
<th>Epsilon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overlying shale</td>
<td>3300</td>
<td>1700</td>
<td>2.35</td>
<td>0.15</td>
<td>0.3</td>
</tr>
<tr>
<td>Gass sand</td>
<td>4200</td>
<td>2700</td>
<td>2.35</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Synthetics generated with Zoeppritz and Aki-Richards methods for both isotropic and anisotropic models.
The amplitude picked from the previous slide. Both Zoeppritz and Aki-Richards methods tend to show more AVO effect in anisotropy.
Comparisons of synthetics generated with Zoeppritz and Elastic Wave modeling (FEW) methods for both isotropic and anisotropic models.
Comparisons of the amplitudes picked from the results of Zoeppritz and Elastic Wave modeling. They agree well on isotropic case but show opposite AVO effect in anisotropy.
The discrepancy between the results of Zoeppritz and Elastic Wave modeling is obvious. To understand what caused the discrepancy we must first review the assumptions the two methods.

(The first thing come to my mind in seeing this discrepancy is that there must be a sign error in the elastic wave modeling code. I spent a few days try to debug the code but find no error. I have no other choice but to think a little bit more in physics.)
Elastic Wave modeling calculates spherical wave propagation.

Zoeppritz modeling calculates plane wave propagation.
In case of isotropic media, the plane wave and spherical wave are equivalent in terms of travel time and incident angle.
In case of anisotropic media, the plane wave and spherical wave are not equivalent neither in travel time or incident angle.
The wave front in the test model (δ=0.15, ε=0.3) is shown below. It has the similar oval shape as indicated in the cartoon shown in the previous slides. Therefore actual incident angle is smaller than the incident angle predicted by plane wave.
We may understand that the anisotropy will affect reflected seismic wave in two ways:

- Effect on reflection coefficients.

- Effect on wave propagation (that is on incident angle).
Explanation of the discrepancy:

For the test model shown above, the reflection coefficient decreases with incident angle. With the same incident angle, anisotropic effect makes the reflection coefficient decrease more than isotropic case. This is what we have in Zoeppritz modeling result.

When the wave front has an oval shape, the incident angle tends to become smaller than that in isotropic case (or plane wave case). This give a counter effect on AVO. The overall effect may result in a less decreased amplitude than the isotropic case. This is what we have in Elastic Wave modeling result.
To test AVO effect due to wave propagation in anisotropic media, I modified the Elastic Wave modeling program to let the wave propagate in isotropic media (anisotropy is ignored when calculate wave propagation) but reflected on the interface of anisotropic media (anisotropy is considered when calculate reflection coefficients). Since I cannot verify the above explanation from another independent source, I am taking this test as a support to the argument that the effect of wave propagation could greatly affect the AVO.
The result of the above described test is shown in the panel marked few_test. By taking away the effect of anisotropic wave propagation it shows a very similar result as Zoeppritz.
Comparisons of the amplitudes picked from the results of the above described test (marked few_test) and the other previous results. It agrees with Zoeppritz very well.
It is not a general conclusion that the incident angle become smaller in anisotropic media. It could become smaller or bigger depending on the shape of wave front. The examples on the right show different wave front shape corresponding to different $\delta$ and $\varepsilon$. 

\[
\begin{align*}
\varepsilon &= \delta = -0.2 \\
\varepsilon &= \delta = 0.2 \\
\varepsilon &= -0.2; \delta = 0.2 \\
\varepsilon &= 0.2; \delta = -0.2
\end{align*}
\]
In the example given in the previous slide, when $\delta = \varepsilon = -0.2$, the wave travels faster in vertical than horizontal direction. In this case the incident angle of plane wave become smaller. We would expect a larger AVO effect in the result of Elastic Wave modeling.
A model with different $\delta$ and $\varepsilon$

<table>
<thead>
<tr>
<th>Materials Properties</th>
<th>$V_p$ (m/s)</th>
<th>$V_s$ (m/s)</th>
<th>Density</th>
<th>Delta</th>
<th>Epsilon 1</th>
<th>Epsilon 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overlying shale</td>
<td>3300</td>
<td>1700</td>
<td>2.35</td>
<td>-0.2</td>
<td>-0.2</td>
<td></td>
</tr>
<tr>
<td>Gas sand</td>
<td>4200</td>
<td>2700</td>
<td>2.35</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Synthetics generated with Zoeppritz and Elastic Wave modeling methods for both isotropic and anisotropic models displayed in the last slide. As expected, we see more AVO effect in Elastic Wave modeling result.
The amplitude picked from the previous slide. The Elastic Wave method tend to show more AVO effect than Zoeppritz. (I don’t know what caused the change at offset 1300 in elastic wave modeling result. More investigation is needed to determine if it is an artifact.)
According to the previous discussion the discrepancy between Zoeppritz and Elastic Wave modeling happens when the wave front deviate from the exact spherical wave front, which can be well approximated by plane wave. For some particular type of anisotropy, ie. $\varepsilon=-0.2$ and $\delta=0.2$, the wave front is close to isotropic wave front when incident angle is small (see plot below). Can Zoeppritz modeling work well in this situation?
A model with $\varepsilon < 0$ and $\delta > 0$

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<tr>
<th>Materials Properties</th>
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<td>0</td>
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</table>
Synthetics generated with Zoeppritz and Elastic Wave modeling methods for the model displayed in previous slide. The offset range from 0 to 2000 except few_iso that is from 0 to 1500. (A NMO under-correction happens at far offset in few_test3_aniso.)
The amplitude picked from the previous slide. The Elastic Wave response shows less AVO effect in small offset and more AVO effect in large offset. Such change agrees with the shape of the wave front displayed in slide 25.
Can Zoeppritz be used in anisotropic modeling?

The previous discussion shows that Zoeppritz modeling has an opposite AVO response than Elastic Wave modeling. This could be misleading in AVO interpretation. Is there any situation that Zoeppritz modeling will have the same AVO response with Elastic Wave modeling?

Using Blangy type II water sand model as an example that has a decreasing AVO effect than its isotropic model. As we discussed before Elastic Wave modeling has a decreased AVO effect. Therefore we expect to see both Zoeppritz and Elastic Wave modeling show the same trend of decreased AVO response for the type II water sand of Blangy model.
Another Blangy’s model

(Type II water sand)

<table>
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<th>Materials Properties</th>
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<th>Delta</th>
<th>Epsilon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overlying shale</td>
<td>2896</td>
<td>1402</td>
<td>2.25</td>
<td>0.15</td>
<td>0.3</td>
</tr>
<tr>
<td>Water sand</td>
<td>3322</td>
<td>1402</td>
<td>2.25</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Synthetics generated with Zoeppritz and Elastic Wave modeling methods for both isotropic and anisotropic models displayed in last slide. As expected, we see decreased AVO effect in both modeling results.
The amplitude picked from the previous slide. The both methods tend to show less AVO effect than isotropic case.
• Effect of anisotropy on AVO is two fold: one is due to change in reflectivity, and the other is due to the shape of the incident wave front. It is important to take the second into account when the overburden is anisotropic.

• For a simple model, the shape of incident wave front is determined by anisotropic parameters $\delta$ and $\varepsilon$ in overburden. When $\delta>0$ or $\varepsilon>0$, AVO effect decreases. When $\delta<0$ or $\varepsilon<0$, AVO effect increases.

• Zoeppritz and A-R modeling methods should be used with caution in anisotropic modeling. The effect due to the shape of incident wave front need to be carefully considered.
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- Kuala Lumpur, Malaysia: +60 3 2382 1100  
  support@email.com
  support@email.com
- Moscow, Russian Federation: +7 495 789 9420 Ext 123  
  support@email.com
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  support@email.com
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