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Modified Anisotropic Walton Model for Consolidated Siliciclastic Rocks: Case Study of Velocity Anisotropy Modelling in a Barents Sea Well

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Summary

The anisotropic Walton model is proposed by Bandyopadhyay (2009), to model the stress-induced anisotropic seismic response of a rock. However, this model is only proposed for unconsolidated rocks, and has only been tested on laboratory data. This work extends the anisotropic Walton model using a test on a well in the Barents Sea. We demonstrate that this model gives a good velocity prediction for shallow unconsolidated rocks, but greatly underestimates the velocities for deeper consolidated rock. For the consolidated rock, we can adjust the velocities from the Walton model with compaction factors, in order to produce reasonable velocity and anisotropy predictions. The compaction factors are primarily dependent on depth, effective porosity, and clay volume, in decreasing order of importance. Facies dependent compaction factors can also be defined to allow us obtain values varying according to lithofacies distribution.
Introduction

Contact models typically assume the rock matrix is a random pack of solid grains, or spherical particles. The effective elastic properties depend on normal and tangential contact stiffness of a two-particle combination. These models provide an analytical treatment of mechanical grain interactions under stress. However, most of the models only model isotropic media, although a few can be extended to the anisotropic case. For example, the Walton model can be extended for anisotropic modelling by assuming a rock under non-hydrostatic stress conditions, as proposed by Bandyopadhyay (2009).

Velocity anisotropy due to the stresses imposed from tectonic sources has been observed in recent years. Reservoir rocks become elastically anisotropic under non-hydrostatic stress. Such a stress makes the distribution of the contact forces anisotropic, and as a result, seismic wave speeds become directionally dependent. The anisotropy could produce a strong influence on seismic data, consequently, on the interpretation of the data by the imaging process. Ignoring the anisotropy effects, we may incorrectly image the reservoir subsurface. However, the anisotropy parameters have been poorly understood in seismic imaging and interpretation. In this work, we will explore the anisotropic Walton model (Bandyopadhyay, 2009) through a test on the data from a well in the Barents Sea. We then extend this model with the concept of compaction factors, in order to apply it to deep, consolidated rocks. We also investigate the physical meaning of the compaction factors by linking them to lithofacies, lithology, and petrophysical properties. The improvements of the Walton model provide good opportunities to quantitative analysis and interpretation of the stress-induced velocity anisotropy in seismic reservoir characterization.

Anisotropic Walton Model

The Walton model assumes the normal and shear deformation of a two-grain combination occurs simultaneously on a random pack of identical spherical grains. Under hydrostatic pressure, the elastic properties of a grain pack are isotropic. If the applied stress is non-hydrostatic then the medium becomes elastically anisotropic. When the horizontal stress is the same in all directions, then the rock becomes vertical transversely isotropic (VTI). Bandyopadhyay (2009) provides explicit closed-form solutions for stress-induced anisotropy in unconsolidated sandstones under triaxial stress for VTI media. Two different scenarios are considered, (a) Grains having infinite friction at the grain contacts – the rough model and (b) grains having zero friction at the grain contacts – the smooth model.

The anisotropic model makes two assumptions: the model is appropriate for weak stress induced VTI anisotropy rocks only, and does not apply in strongly anisotropic media, such as in the case that the ratio of vertical to horizontal strain is extremely large or small; secondly, the model applies to unconsolidated rocks only. The assumption of weak VTI anisotropy should be valid for most rocks, if the rock has not undergone a complex mechanical process, such as fault dislocation. However, the second assumption cannot be guaranteed, since most of our reservoir rocks are buried in deep formations with strong compaction effects, thus becoming very consolidated.

We design a theoretical test to demonstrate the modelled VTI anisotropy from the anisotropic Walton model. Here we assume a random pack of identical spherical grains under non-hydrostatic strain (vertical and horizontal strain are different). The porosity of this pack of quartz grains is 0.38, the coordination number is 8, the horizontal strain is fixed to be 0.005, and we vary the vertical to horizontal strain ratio from 0.5 to 2. The anisotropic velocities are modelled as the vertical to horizontal strain varies (Figure 1).
In Figure 1, we can see that the rough contact model gives higher velocity than the smooth contact model. Also, the fast and slow velocity changes when the ratio of vertical to horizontal strain varies from 0.5 – 2. They are the same (isotropic) when the ratio becomes 1. Such observations match with our general understanding about anisotropic media, therefore, validate the modelling algorithm.

Well Data Application and Improvement

We apply the Walton model on log measurements from a well in the Barents Sea: 7220/4-1. This well was drilled in the Johan Castberg area and encountered gas in the Sto, Nordmela and Tubaen formations. The logs have been carefully conditioned prior to rock physics modelling. Figure 2 shows the conditioned suites of logs. Two zones of interest (ZOI) with good dipole shear measurements are identified (marked by blue boxes). One is a shallow interval (750–1250 m), and consists of porous and unconsolidated rock, mostly shale. The other is a deeper interval (2513–3240m), and comprises tight, consolidated rock, mostly sand and siltstone. To remove the gas effect, reservoir zones (Sto, Nordmela and Tubaen formations) are not included. The other gas saturated rocks in the deep interval are also excluded for this study.

One of the most important inputs for this model is the stress in the vertical and horizontal directions. It is common practice that the vertical stress is calculated using the density log. However, there is no equivalent method to calculate the horizontal stress, therefore, we choose to set the horizontal to vertical stress ratio as one of fitting parameters, to match the modelled velocity with the measurements. Figure 3 shows the modelling results using the Walton model (rough contact) in both intervals.

**Figure 1** Anisotropic Walton modelling for a random pack of quartz grains. a) P-wave velocity vs. vertical to horizontal strain. b) S-wave velocity vs. vertical to horizontal strain.

**Figure 2** The log data for well 7220/4-1 in the Barents Sea. Vs-C44, and Vs-C66 are the shear velocity calculated from the C44 and C66 tensor which can be estimated from dipole shear and Stoneley wave data (White, 1983). Two zones of interest are marked by blue boxes.
Figure 3 Modelling results using the Walton model (rough contact) in both intervals. The black curves are the in-situ measurements, and the red curves are the modelled velocities.

In the shallow interval, we can see the modelled velocity matches the measurements very well. However, in the deep interval, the Walton model greatly underestimates the velocities, simply because the Walton model assumes that the rock is unconsolidated, which is more or less valid in the shallow section, but may not be valid in the deeper section. To adjust the Walton model for the consolidated deep rocks, we need to introduce compaction factors to correct the velocities from the model.

Figure 4 shows the modelling results from the modified Walton model, with compaction factors shown in the right track. Similar to the horizontal stress, the correction factors are chosen as fitting parameters, in an effort to match the measurements. Since the original velocity from the Walton model is lower than the measurement, the correction factors are always larger than 1. Note that we have to use different compaction factors for Vp and Vs, which may suggest compressional and shear velocity cannot be modelled consistently from the original Walton model (Bandyopadhyay, 2009).

Figure 4 Modelling results from the modified Walton model (rough contact) in the deep consolidated rocks, with compaction factors shown in the right track.
Compaction Factors

In this section, we will explore the physical meaning of compaction factors, and try to link these factors to facies, lithology, etc. Figure 5a shows the cross-plots of the compaction factors and effective porosity, color-coded by clay volume. For the consolidated (deep) rock, the correction factors are different according to the effective porosity, and clay volume. Effective porosity seems to be the main driver, which is used to divide these rocks into 3 categories: porous rock, medium rock, and tight rock; For tight rock, there is a clear clay effect, so it is further divided as tight shale and tight siltstone; However, we can observe that as the rock becomes tighter, the scatter in these factors increases. Based on our observations, facies dependent factors are assigned in Figure 5b.

![Figure 5 Compaction factor analysis. (a): cross-plots of the compaction factors and effective porosity, color-coded by clay volume for compressional (top) and shear (bottom) velocity. (b): Facies-dependent compaction factors.](image)

Figure 6 shows the similar exercise using the facies-dependent compaction factors as defined in Figure 5b to model the deep consolidated rocks. Overall, the modeling of the velocity and anisotropy have a fair/good agreement with the measurement.

![Figure 6 Modelling results from the modified Walton model (rough contact) in the deep consolidated rocks, with facies-dependent compaction factors shown in the right track.](image)

Conclusions

The anisotropic Walton model works well for unconsolidated rocks, but underestimates the velocities for consolidated rocks. For consolidated rocks, we introduce compaction factors to improve the Walton model for better velocity and anisotropy modelling. The factors are facies-dependent, so they can be adjusted to allow us to obtain more accurate modelled values as a function of lithofacies distribution.

References