Ottawa sand-Revisited: Aspect of fluid substitution

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Summary

Laboratory measurements of ultrasonic P-and S-wave velocities were performed on unconsolidated dry and saturated clean Ottawa sands under uniaxial strain and hydrostatic stress conditions. The behaviour of wave modulus and anisotropic parameters under stress upon fluid saturation is investigated. Besides this paper addresses the basics assumptions of the Gassmann theory, in order to see how well they are fulfilled in controlled laboratory experiments. As expected plane wave modulus is found to be fluid sensitive. However, Shear modulus hardening also observed. All the anisotropic parameters (P-wave anisotropy, $\varepsilon$; Move-out parameter, $\delta$; Anellipticity, $\eta$ and even S-wave anisotropy, $\gamma$) are found to be sensitive to fluid. It is observed that Gassmann's fluid substitution theory under predict the P-wave modulus and this can be compensated by the effect of dispersion. The cause of shear modulus hardening also can be attributed to the dispersion. The effect of dispersion is also visible in $v_p$–$v_s$ relations.

Introduction

Change in fluid saturation generally occurs in reservoir due to production and injection of fluid. Therefore, it is important to know the changes (velocity, density etc.) in the reservoir due to change in fluid content. In 4D seismic, changes in seismic velocities and reflection coefficients related to changes in fluid saturation are quantified using Gassmann fluid substitution theory (Landrø 2001; Gassmann 1951). According to Gassmann's fluid substitution, shear modulus is insensitive to change in fluid. However, from the laboratory experiments, Domenico (1977); Khazanehdari & Sothcott (2003); Baechle et al. (2009); Adam et al. (2006); Fabricius et al. 2010 it is found that the shear modulus in different porous rocks may show hardening or softening effect upon saturation. This paper made an attempt to investigate the share modulus hardening effect on well characterized material under control laboratory measurements.

The change of fluid also affects the anisotropic parameters of the reservoir along with velocity and density change. Implementation or incorporation of anisotropy is generally ignored due to the difficulty in obtaining all the elastic coefficients to characterize the anisotropy and complexity to implement. However to achieve high quality seismic imaging to visualize the complex structures it is important to incorporate anisotropy. Besides, the knowledge of anisotropy may improve 4D and/or quantitative AVO interpretation. Understanding the changes of anisotropic parameters with stress/depth as well as upon change in fluid saturation is essential for better imaging and for 4D and/or quantitative AVO analysis. All the anisotropic parameters are quantified (5 elastic stiffness) for both
dry and saturated Ottawa sand to improve the knowledge of the behavior of anisotropic parameter upon saturation.

Methods

Five Ottawa sands (subrounded) of different grain sizes are used to investigate the shear modulus hardening/softening upon fluid saturation and $v_p$ and $v_s$ relation. However, only one sample is investigated to measure the effect of fluid on anisotropy parameter. 3.5wt% NaCl is used as saturating fluid. The dry samples are dried in oven at 110ºC. The dry samples are prepared/reconstructed using the same technique as Ruiz (2003).

Table 1: Ottawa sands used in this study

<table>
<thead>
<tr>
<th>Name</th>
<th>Grain Size</th>
<th>Grain shape</th>
<th>Initial porosity@0,7MPa (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ottawa Sand*</td>
<td>450-210 μm</td>
<td>Sub-rounded to rounded</td>
<td>37.4</td>
</tr>
<tr>
<td>Ottawa Sand</td>
<td>&lt; 230 μm</td>
<td>Sub-rounded to rounded</td>
<td>38.2</td>
</tr>
<tr>
<td>Ottawa Sand</td>
<td>355-230 μm</td>
<td>Sub-rounded to rounded</td>
<td>37.2</td>
</tr>
<tr>
<td>Ottawa Sand</td>
<td>450-355 μm</td>
<td>Sub-rounded to rounded</td>
<td>37.0</td>
</tr>
<tr>
<td>Ottawa Sand</td>
<td>&gt; 450 μm</td>
<td>Sub-rounded to rounded</td>
<td>36.8</td>
</tr>
</tbody>
</table>

* is the only sample performed in Triaxial test system.

Two test setups have been used namely, 1. Oedometer test system and 2. Triaxial test system. The effect of fluid on anisotropic parameters is measured in Triaxial test system and the rest (shear modulus hardening/softening, $v_p$ and $v_s$ relation) are measured in Oedometer test system. In Triaxial test system, both uniaxial strain and hydrostatic stress condition are employed whereas only uniaxial strain condition can be investigated in Oedometer test system. The sample is 38mm in diameter and 60-65mm in length in the Triaxial test system and 70mm in diameter and 25-30mm in length in the Oedometer test system. Both dry and saturated tests were performed in a single run for each of the tests. In Oedometer, the samples were saturated after two cycles of loading and unloading in dry conditions. After achieving complete saturation, the pore pressure (0.5 and/or 1.0 MPa) was kept constant for one loading and unloading cycle in saturated conditions. Only vertical P and S-wave velocities along with horizontal P-wave velocities were measured.

In triaxial test system, after two hydrostatic stress and uniaxial strain cycles in dry conditions (vacuum during dry test only), the samples were saturated with 3.5 wt% brine and maintain constant pore pressure for two more cycles in uniaxial strain and one cycle in hydrostatic stress condition. Both vertical and horizontal P-and S-wave velocities were measured. Moreover, P-wave at 20, 37, 47, 68 degree angles are also measured. Detail can be seen in Bhuiyan et al. (2013).

Results

Shear modulus hardening is observed for the samples tested in Oedometer test system. The observation is consistent to all the five samples. Investigation shows that Biot or global dispersion is the prime mechanism to cause shear modulus hardening.
Figure 1. Dispersion corrected shear modulus plotted against dry shear modulus to show the effect of dispersion due to global flow mechanism. Red symbols are original data and blue symbols are dispersion corrected data (Tortuosity factor =2).

Experiment shows that the values of P-wave anisotropy and delta decrease upon fluid saturation. However, surprisingly, shear modulus also showed fluid dependence and increase (absolute values) upon saturation. Eta also found to be sensitive to fluid saturation. Relation suggested by Collet and Gurevich (2013) may also be verified using the experimental data.

Figure 2. Eta calculated using equation (12) for both dry and saturated sand. Equation (14) shows the relationship between dry and saturated eta. This figure shows that this equation is valid for sand.
The $v_p - v_s$ relation is strongly dependent on fluid saturation. $v_p/v_s$ is almost constant for dry samples whereas increase with decrease in net stress for saturated samples. It has found that Biot dispersion is required to explain the experimentally measured saturated $v_p - v_s$ relations.

Conclusions

1. Shear modulus hardening is observed upon fluid saturation and can be attributed to the velocity dispersion.
2. Anisotropic parameters are found to be sensitive upon fluid saturation, even the theoretically fluid insensitive gamma.
3. $v_p - v_s$ relations is strongly sensitive to fluid.

Acknowledgements

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References


