AN ELASTIC PROPERTIES COMPUTATION TO PREDICT 4D SEISMIC EFFECTS FOR CO₂ SEQUESTRATION – A METHODOLOGY

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SUMMARY

Within Otway Basin CO₂ sequestration program, a small amount of CO₂ is currently being injected into a depleted Naylor gas field, onshore Victoria. The reservoir is relatively deep (2 km) and complex with area extent of approximately 0.5 km² limiting the monitoring program to the application of seismic methods only. However the injection of CO₂ into this heterogeneous reservoir, where residual gas saturation is present throughout most of the sand column, is expected to cause very subtle changes in elastic properties of the reservoir rock. Indeed initial approximate modelling of 4D seismic response showed that only 4-6 % change in the elastic parameters could be expected. Such small effect could be “lost” even through approximate fluid substitution methodology. Considering inherently low repeatability of land seismic it becomes even more important to accurately predict 4D seismic at this site. For that purpose we have investigated various methodologies that could increase the accuracy of the predicted changes in elastic properties of the reservoir rock. We derived a methodology for accurate prediction of elastic properties of the reservoir rock through calibration of the log and petrophysical data with core sample. The result showed core saturated velocities and log measurement agree with each other when the “effective” K_{grain} is applied. It suggested that “effective” K_{grain} could be used to represent the average mineralogy of the grains if we do not know the exact mineral composition making up the rock. However, comparative analysis and calibration of log measurement with core sample proved that accurate fluid substitution methodology at this site is hard to achieve without having dense core sample test results within the reservoir interval. In this paper, we present a methodology to derive elastic properties of the reservoir rock through calibration of the log and petrophysical data with core sample measurement.

INTRODUCTION

In most applications of Gassmann's equation, only the bulk modulus of the dry-rock (K_{dry}) is measured. Properties of the mineral grain modulus (K_{grain}) are often poorly understood and oversimplified. K_{grain} is the modulus of the solid material that includes grains, cements and pore fillings. If clays or other minerals are present with complicated distributions and structures, K_{grain} can vary depending on mineral composition, distribution of the grains and in-situ conditions. As a result, the calculated velocity will differ from the log velocity.

Recent work by Marcos et al. (2008) showed that core saturated velocities agreed with log measurements at reservoir interval when using representative K_{grain} .

Dry-core measurements of the reservoir rock were carried under room conditions. We obtained the dry bulk moduli from core measurement and derived the “effective” grain mineral modulus (K_{grain}) using forward Krief as a function of dry-rock modulus and “exact” porosity. Then we applied Gassmann’s equation to calculate low-frequency saturated velocities from dry core measurement at in-situ reservoir saturation and pressure.

The saturated velocities from dry core and log measurement agree with each other when the “effective” grain mineral modulus (K_{grain}) is applied. Deriving the dry moduli helps us to validate the input parameters and output results of Gassmann’s calculation. As a result, knowing the “effective” grain mineral modulus (K_{grain}) improved the accuracy of interpreting the fluid substitution and 4D seismic effect for CO₂ sequestration monitoring program. The later can guide modelling and inversion process.

Here we investigated and obtained accurate prediction of elastic properties through calibration of the log and petrophysical data with core sample. To validate the calculation, we compared the core saturated velocities at in-situ reservoir condition with log measurement.

NAYLOR RESERVOIR

The Naylor Gas Field is a small field with a single depleted gas well called Naylor-1. The field is located in the onshore of Otway Basin in Victoria, Australia. The reservoir itself, Waarre Sandstone unit C (Waarre-C Sandstone), is situated in a tilted fault block. It is approximately 25 m thick with clay intercalations and is sealed by a thick and massive Belfast Mudstone and bounded by major faults. Reservoir sand has relatively good porosity and high but variable permeability (100 mD to 4 D). Figure 1 shows a representative core sample within reservoir interval with fine to coarse grained, massive, quartz of good porosity. Waarre-C Sandstone was considered as a good medium for CO₂ injection and monitoring program.

Figure 1: Representative core sample of Waarre Sandstone unit C at 2071.5 meter depth, with fine to coarse grained massive, quartz dominant and good porosity (21.1%).

CRC-1 was drilled in 2007, some 300 m away from the Naylor 1 well. CRC-1 is the injection well for CO₂ sequestration monitoring program. Naylor-1 well is equipped for monitoring. Complete set of wireline logs was recorded in CRC-1 including several core samples taken reservoir sand and overlying sealing shale formation.

After production and before injection, the reservoir sands at CRC-1 are 80% water-saturated with 20% residual gas remaining in the pore space. Reservoir pressure is around 2580 psi (17.6 MPa) and temperature is 85°C. The injection of CO₂ will displace the in-situ reservoir fluid (brine and CH₄) around area of CRC-1, and due to buoyancy it will migrate towards the monitoring well (Naylor-1), where CO₂ will be trapped underneath the remaining CH₄ cap (density segregation). Within 12 months of monitoring program, it is expected that reservoir sand at CRC-1 will be 85% gas-saturated (CO₂ dominant), with 15% of water remaining. Schematic flow of CO₂ sequestration monitoring program is shown by Figure 2.

Figure 2: Schematic flow of CO₂ sequestration monitoring program in Otway Basin. Buttress-1 well is the source of CO₂ production.

METHODOLOGY

The potential error in computation of bulk moduli in the case of CRC-1 reservoir with only logs is high unless we can use calibration with core sample. Therefore, to obtain elastic properties of reservoir rock we did the following:

1. Perform dry core measurements to obtain the relationship between effective pressure and velocities.
2. Calculate K_{dry} from dry core measurement.
3. Derive K_{grain} using inverse Krief (porosity is measured).
4. Apply Gassmann's equation to compute core saturated velocities from the dry core measurement at in-situ reservoir condition ($S_w = 98.53\%$).
5. Apply Gassmann's equation to compute bulk modulus of saturated porous rock (K_{sat}) from log measurement.
6. Compare the calculated core saturated velocities with log measurement (sonic log).

We used some basic and petrophysical logs such as gamma ray, velocity, density, porosity, saturation, resistivity, clay volume and caliper to analyse and interpret the reservoir (Figure 3).

Figure 3: Composite logs that show reservoir interval and depth of core sample. Yellow box is the interval where the core plug was taken and measured.

Core plug was taken from 2071.5 m depth. Ultrasonic measurements were performed under room conditions, with confining pressures up to 55 MPa in steps of 5 MPa. The result in Figure 4 showed measured dry and water-saturated P- and S-wave velocities of Waarre-C sandstone as a function of effective pressure. The difference in S-wave velocity for dry and water-saturated cases is higher than for P-wave velocity, which shows that the density effect dominates. This is consistent with the initial computations for Naylor-1 well and CRC-1 well (Li et. al., 2006; Wisman et. al., 2007).

Figure 4: Measured P- and S-wave velocities at dry and water-saturated states with 98.53% of water saturation, as a function of effective pressure. The difference in S-wave velocity for dry and water saturated cases is higher than P-wave velocity, which shows that the density effect dominates.

The core measurements provided relationships between seismic velocities and effective pressure (P_{eff}) of the dry Waarre-C sandstone:

$$V_{pdry} = 2654.1 P_{eff}^{0.0934} (m/s), \quad (1)$$

$$V_{sdry} = 1460.3 P_{eff}^{0.1399} (m/s) \quad (2)$$

The estimated effective pressure at reservoir level is 27.25 MPa. The dry velocities were calculated using equation (1) and (2) are showed in Table 1a; and moduli in Table 1b.

Sample depth (m)	Vpdry (m/s)	Vsdry (m/s)	Rhdry (g/cm ³)	Core grain density (g/cm ³)	Core porosity (%)
2071.5	3613.936	2318.7283	2.083749	2.641	21.1

Table 1a: Calculated dry velocities at estimated reservoir effective pressure (27.25 MPa) incorporated with core porosity and core grain density measurement at 2071.5 meters depth.

Sample depth (m)	Kdry (GPa)	Mudry (GPa)	Kgrain (GPa)	Mugrain (GPa)
2071.5	12.2772	11.2033	30.2302	27.5860

Table 1b: Calculated dry moduli and mineral grain moduli at estimated reservoir effective pressure (27.25 MPa) derived from inverse Krief formula at 2071.5 meters depth.

COMPUTATION OF ELASTIC PROPERTIES

We applied Gassmann's equation to calculate the effective bulk and shear modulus of saturated porous rock taken into account the dry core measurements using the following equation:

$$K_{sat} = K_{dry} + \frac{\left(1 - \frac{K_{dry}}{K_{grain}}\right)^2}{\frac{\phi}{K_{fluid}} + \frac{1-\phi}{K_{grain}} - \frac{K_{dry}}{K_{grain}^2}}, \quad (3)$$

$$K_{dry} = \rho_{dry}(V_{pdry}^2 - 4V_{sdry}^2 / 3), \quad (4)$$

$$\mu_{dry} = V_{sdry}^2 \rho_{dry}, \quad (5)$$

where K_{grain} , K_f , K_{dry} , K_{sat} , are the bulk moduli of the mineral grain, fluid, dry rock, and saturated rock frame, respectively; and ϕ is porosity. V_{pdry} , V_{sdry} are P- and S-wave velocities of the dry rock from core measurement, respectively calculated from equation (1) and (2); ρ_{dry} is the density of dry rock.

Using saturation log, we calculated bulk modulus of pore fluids, K_f using Wood's equation:

$$\frac{1}{K_f} = \frac{S_w}{K_w} + \frac{S_g}{K_g}, \quad (6)$$

where K_w and K_g are the bulk moduli of water and gas, respectively; S_w and S_g stand for water and gas saturation ($S_g = (1 - S_w)$). This assumes that the fluid is uniformly distributed within pores.

Knowing the “exact” porosity and K_{dry} from dry core measurement, we derived “effective” K_{grain} with the following equation:

$$K_{grain} = K_{dry} / (1 - \phi)^{\frac{3}{(1-\phi)}} \quad (7)$$

The “effective” K_{grain} is then used to calculate saturated velocities from dry core measurement and bulk modulus of saturated porous rock.

To obtain K_{dry} from log measurement, we used inverse Gassmann's equation as follow:

$$K_{dry} = \frac{K_{sat} \left(\frac{\phi K_{grain}}{K_f} + 1 - \phi \right) - K_{grain}}{\frac{\phi K_{grain}}{K_f} + \frac{K_{sat}}{K_{grain}} - 1 - \phi}, \quad (8)$$

For K_{sat} , we use the equation:

$$K_{sat} = \rho_{sat} (V_{psat}^2 - 4V_{ssat}^2 / 3)$$

$$\mu_{sat} = V_{ssat}^2 \rho_{sat}, \quad (9)$$

(10)

where V_{psat} , V_{ssat} are P and S-wave velocity of saturated rock, respectively (log measurement);

$\mu_{sat} = \mu_{dry}$ is shear modulus of saturated/dry rock frame and ρ_{sat} is bulk density of saturated rock.

Finally, for saturated core, we calculate velocities as:

$$V_{psat} = \sqrt{\frac{K_{sat} + \frac{4}{3}\mu_{sat}}{\rho_{sat}}} \quad \text{and} \quad V_{ssat} = \sqrt{\frac{\mu_{sat}}{\rho_{sat}}} \quad (11)$$

SENSITIVITY ANALYSIS

In practice, the measurements are always made with some errors. The problem arises when the input errors are so large that values of the calculated elastic moduli become unreliable. To gain insight into the effect of input errors onto the computation of elastic properties for this area we performed sensitivity analysis. For that purpose we calculate the difference in the elastic properties under in-situ reservoir condition with respect to 10% errors in “effective” K_{grain} .

This analysis showed 10% error in “effective” grain mineral modulus produces small effect on velocity calculated with Gassmann, but produces a very large velocity error when using Krief. Hence estimating the grain mineral modulus accurately will provide flexibility in calculation and also minimize fluid substitution modelling errors (Figure 5).

Figure 45: The different between V_p core saturated (V_p Krief and V_p Gassmann) and V_p log using varied K_{grain} . $K_{grain} = 30.2310588$ GPa suggested both velocities (Krief and Gassmann) agreed (0.03%).

RESULTS

Figure 6 shows core saturated velocities agreeing with log measurements after applying “effective” K_{grain} . “Effective” K_{grain} was 30.23015888 GPa with 98.53% water saturation at 2071.5 meter depth. The velocity calculated differ for only 1.1 m/s (0.03%) from V_p log (V_p core saturated - 3566 m/s, V_p log - 3567.1 m/s).

Figure 56: V_p core saturated (red dot) and V_p log measurement showed almost no difference after applying “effective” K_{grain} .

CONCLUSIONS

We have described a methodology for accurate prediction of elastic properties of the reservoir rock through calibration of the log and petrophysical data with core sample if we do not know the exact mineral composition making up the rock. We propose forward Krief modeling to be used to obtain “effective” K_{grain} . Applying “effective” K_{grain} will result in core saturated velocity agreeing with log measurement. However, it requires a dense core sample within the reservoir interval. This may be a problem for Otway project and an alternative methodology may need to be devised.

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