Elastic Property Changes of Bitumen Reservoir duing Seam Injection

Ayato Kato*
University of Houston, Houston, TX
akato@mail.uh.edu

Shigenobu Onozuka
JOGMEC-TRC, Chiba, Japan

Toru Nakayama
JAPEX, Tokyo, Japan

and

Leigh Skinner
JACOS, Calgary, AB, Canada

Summary

Elastic property changes of oil sands reservoir during steam injection are poorly understood. We measured and analyzed ultrasonic velocities of the oil sands and then obtained a relation of the velocities with temperature and pressure individually. We also investigated validity of the Gassmann equation for predicting velocity changes and confirmed that the Gassmann equation can be applicable at temperatures greater than 80 ˚C. We combined the laboratory measurement results to obtain a sequential rock physic model that can predict velocity changes induced by steam injection. We predicted elastic property changes during the steam injection according to the model. P-wave velocity is a relatively all-around player for distinguishing steam fronts, while S-wave velocity can be used only for distinguishing a gentle-warmed area.

Introduction

Heavy oil and bitumen have become tremendously important resources for us in this decade. Properties of them significantly differ from conventional oil. They are characterized by several features; higher viscosity, higher density, higher seismic attenuation, higher velocity dispersive, and so on (Han et al., 2006; Batzle et al., 2006; Mochinaga et al. 2006; Han et al., 2007).

The SAGD method is one of the most effective methods for producing the bitumen in Canada. It makes the bitumen flowable by heating it with injected steam and reducing its viscosity. The steam movement is highly influenced by complex substructure in the reservoir. The time-lapse seismic survey is expected to be powerful for monitoring the three-dimensional steam movement. However, there remain the difficulties of how to make quantitative interpretation of the time-lapse data because there is no model of relating seismic velocities of bitumen-saturated sediments (oil sands) directly with reservoir parameters (temperature, pressure, and saturation). This study aims to obtain a practical model which can predict sequential velocity changes during steam injection.

Oil Sands Sample

We collected whole core of oil sands from the JACOS Hangingstone SAGD operation area in order to measure and analyze P- and S-wave velocities over a range of temperature and pressure. Because the oil sands are easily collapsed at room temperature due to poor-consolidated packing, we froze the whole core right after the core sampling to strengthen its packing by bitumen of which viscosity is increased. We cut the whole cores into blocks and carefully whittled four plug samples from the blocks by lathe. Then, the plug samples were carefully trimmed in order to be held firmly with transducers. The four plug samples are 1.5 inches in diameter and more or less 1 inch in length.

Ultrasonic Laboratory Measurements

We applied the pluse-transmission method to measure P- and S-waves velocity of the oil sands with changing pressure and temperature separately. Figure 1 show the velocities as the function of differential pressure with constant temperature (10 ˚C). The P- and S-wave velocities gradually decrease with decreasing differential pressure. Appling a natural logarithm as a fitting curve, we obtain relationship between velocities and differential pressure,

$$\begin{aligned} V_p &= 0.0593 \cdot Log(P_{diff}) - 0.375 + V_{P0} \\ V_S &= 0.0780 \cdot Log(P_{diff}) - 0.495 + V_{S0} \end{aligned} \quad (1)$$

where P_{diff} is differential pressure (psi), V_P and V_S are P- and S-wave velocities (km/s), and V_{P0} and V_{S0} are P- and S-wave velocities (km/s) at the initial condition (differential pressure of 600 psi and temperature of 10 ˚C).

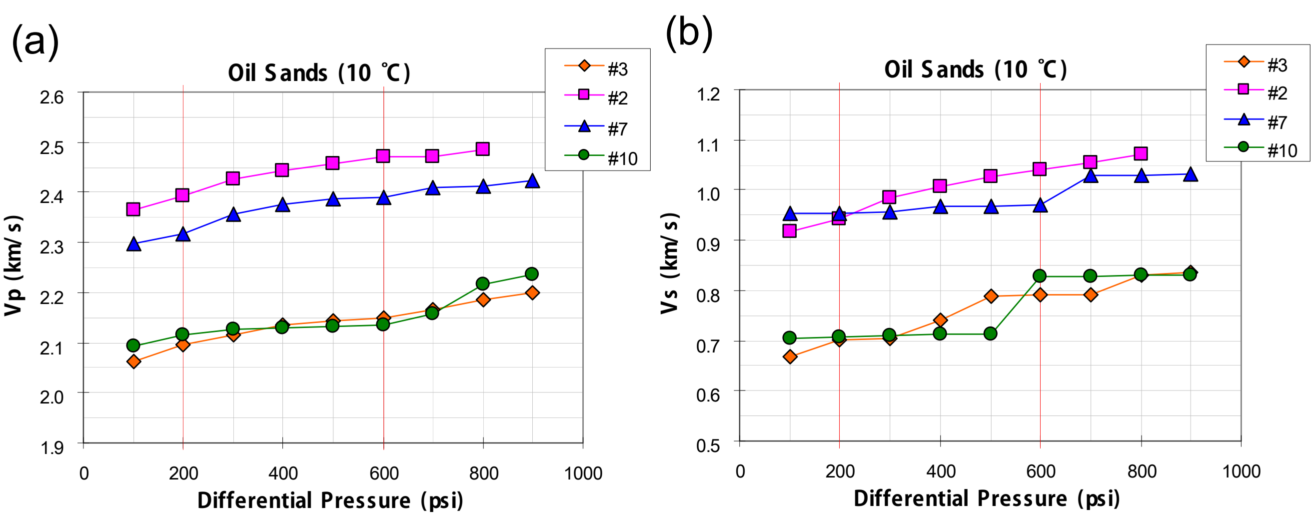

Figure 1: P- and S-wave velocities of the oil sands as the function of differential pressure.

Figure 2 shows P- and S-wave velocities of the oil sands as the function of temperature. Slope of the velocities to temperature significantly changes around 30 ˚C. Whereas P- and S-wave velocities steeply decreases at the lower temperature, P-wave velocity more gently decreases and S-wave velocity remains almost constant at the higher temperature. In the range of the lower temperature, it is considered that bitumen works as pseudo-solid to stiffen grain frame moduli. This remarkable feature of bitumen may make P- and S-wave velocities increase.

We divided the velocities at a given temperature by velocity at 10 ˚C to obtain normalized velocity. The normalized velocities are fitted by two linear lines which cross each other at 30 ˚C.

$$
\begin{aligned}
&T \le 30\ ^\circ\mathrm{C} \\
&\qquad V_P / V_{P1} = -0.0055 \cdot T + 1.06 \\
&\qquad V_S / V_{S1} = -0.0190 \cdot T + 1.19 \\
&T > 30\ ^\circ\mathrm{C} \\
&\qquad V_P / V_{P1} = -0.0017 \cdot T + 0.94 \\
&\qquad V_S / V_{S1} = -0.0006 \cdot T + 0.64
\end{aligned}
\tag{2}
$$

where T is the temperature (˚C), V_{P1} and V_{S1} are P- and S-wave velocities (km/s) at temperature of 10 ˚C and differential pressure of 200 psi.

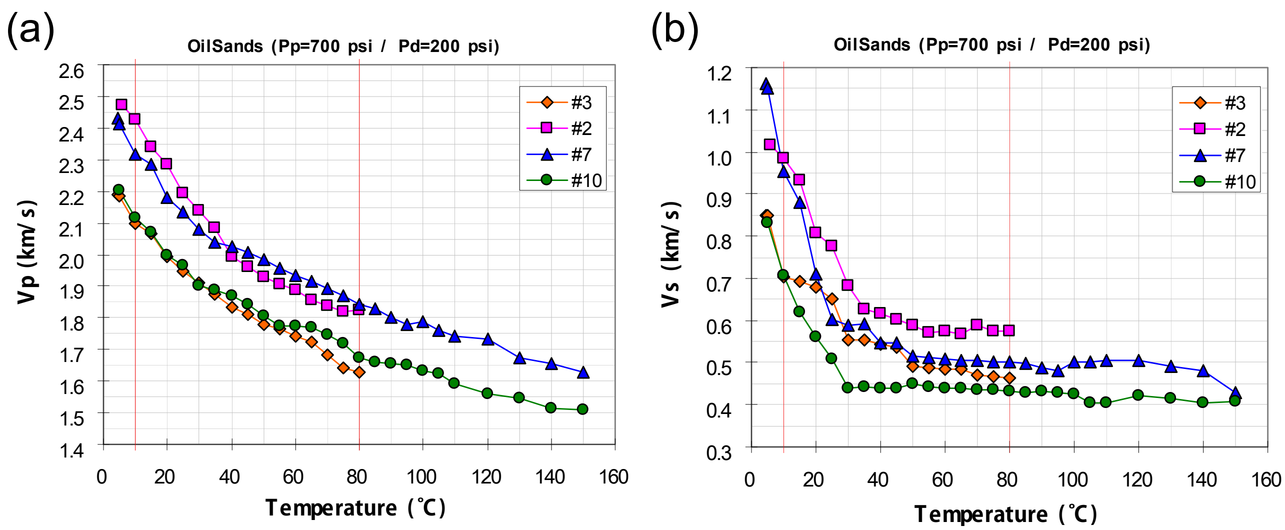

Figure 2: P- and S-wave velocities of the oil sands as the function of temperature.

Application of the Gassmann Equation

We investigated validity of the Gassmann equation for predicting velocity changes. The dry frame moduli calculated based on the Gassmann equation remained almost constant at higher temperature than 80 ˚C and consistent with the theoretical calculation for unconsolidated grain packing. Moreover, velocities at the higher temperatures calculated by the Gassmann equation were fairly consistent with the actual measurement. Consequently, we concluded that the Gassmann equation can be applicable for predicting velocity changes at higher temperatures.

Sequential Rock Physics Model

We combined the laboratory measurement results to obtain a sequential rock physic model that can predict sequential velocity changes induced by steam injection (Figure 3). Once steam is injected to the reservoir, the pressure front rapidly spreads to the periphery, and then the temperature front follows it. P- and S-wave velocities decrease due to the pore pressure increase as a natural logarithm relation with differential pressure. After the pressure change, the velocities decrease with increasing temperature as a linear relation, with a change in slope at 30 ˚C. Moreover, adjacent to injector well, bitumen is replaced by hot water or steam. The velocities at higher temperatures than 80 ˚C can be calculated based on the Gassmann equation.

We assume sequential reservoir conditions and simulate a velocity change under each condition base on the model. In the first pressure change, P- and S-wave velocities decrease. Then, in the next temperature increase, both P- and S-wave velocities significantly decrease, but amount of decrease of the S-wave velocity is relatively larger than the P-wave velocity that Vp/Vs ratio significantly increases. At temperatures greater than 30 ˚C, the P-wave velocity continues to decrease while the S-wave velocity remains almost constant (because shear modulus is thoroughly constant). Moreover, the P-wave velocity slightly increases at 200 ˚C, where bitumen is replaced by hot water which has faster P-wave velocity than bitumen. Finally, the fluid phase change from hot water to steam comes about at 260 ˚C, leading to significant P-wave velocity drop (while the S-wave velocity slightly increases due to a density decrease).

1. Pp 300 psi → 700 psi (at T = 10 C)
   Vp = 0.0593 log (900-Pp) - 0.375 + Vp0
   Vs = 0.0780 log (900-Pp) - 0.495 + Vs0
2. T 10 C → 30 C (at Pp = 700 psi)
   Vp = (-0.0055 T + 1.06) x Vp1
   Vs = (-0.0190 T + 1.19) x Vs1
3. T 30 C → 80 C (at Pp = 700psi)
   Vp= (-0.0017 T + 0.94) x Vp1
   Vs= (-0.0006 T + 0.64) x Vs1
4. T ≥ 80 C Fluid Property Changes
   (associated with T, Sw and phase changes)
   Gassmann eq. can be used to predict velocity change
   Fluid properties are based on FLAG program

Vp0 : P-wave velocity at 300psi & 10 C
Vs0 : S-wave velocity at 300psi & 10 C
Vp1 : P-wave velocity at 700psi & 10C
Vs1 : S-wave velocity at 700psi & 10C

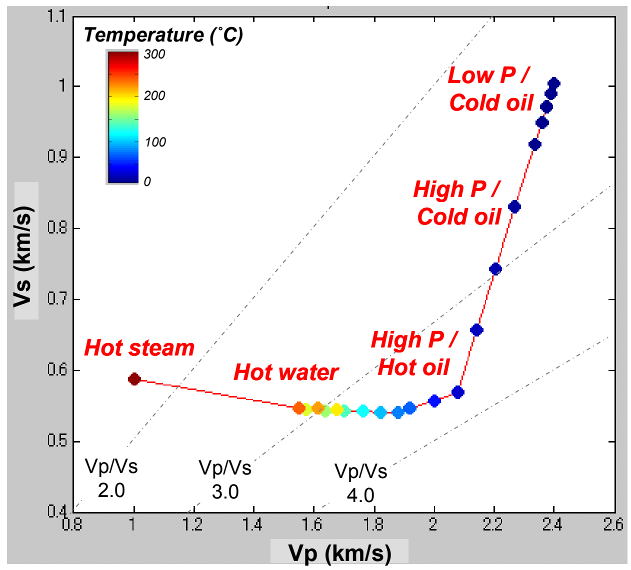

Figure 3: Sequential rock physics model for bitumen reservoir and cross plot between P- and S-wave velocities during steam injection based on the model

Conclusions

We measured and analyzed the ultrasonic velocities of the oil sands acquired from the SAGD operation area and then obtained a relation of the velocities with temperature and pressure individually. We also investigated validity of the Gassmann equation for predicting velocity changes and confirmed it can be applicable at temperatures greater than 80 ˚C. We combined the laboratory measurement results to obtain a sequential rock physic model that can predict velocity changes induced by steam injection. P-wave velocity is relatively all-around player for distinguishing steam fronts because it gradually increases with the increasing distance from the injector. On other hand, the S-wave velocity can be used only for distinguishing gentle-warmed areas.

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