Introduction

The oil recovery rate stays at about 30 to 60 percent even after the secondary oil recovery and is expected enhanced for the effective petroleum production, in which enhanced oil recovery (EOR) has been of great interest. Foam-assisted EOR, one of the EOR methods, has attracted attention for its enhancement in oil recovery rate and sweep efficiency (Talebian et al., 2014). Although many studies related to foam-assisted EOR have been conducted and its mechanisms have been revealed both in macroscopic and in microscopic ways, the method to explore the movement of fluids in reservoir pore spaces and to detect the resulting property change of reservoir has not been fully established yet. The evaluation of EOR effect is mainly conducted by analysing field data obtained by production and injection wells and reservoir simulation. In this situation, we could know the occurrence of fingering or tonguing due to the stimulation by the injected fluids and instability of foam only after it occurred. So, monitoring the advancement of subsurface fluids is important and could be a key technique to improve the efficiency of foam-assisted EOR.

In the previous studies, we conducted numerical experiments to validate the effectiveness of seismic methods to the monitoring of foam-assisted EOR. The obtained results indicated that simple amplitude versus offset (AVO) analysis could capture the position of subsurface foam and advancement of injected fluids (Tamura et al., 2018) and that reverse time migration (RTM) could visualize the replacement of pore fluids of reservoir quantitatively (Tamura et al., 2019). However, we had not investigated the feasibility of the estimation of reservoir property changes caused by the replacement of pore fluids.

In this study, we apply full waveform inversion (FWI) to estimate physical properties of reservoir. We set 2D simulation models assuming time lapse foam-assisted EOR practice and make synthetic data sets using finite-difference method (FDM). Then we apply FWI to the obtained data sets. We investigate the possibility of estimating the property change of the reservoir during foam-assisted EOR using FWI.

Method

In this study, we calculate elastic wave propagation and conduct FWI in frequency domain. Following equations are the elastic wave equation in frequency domain. Figure 1 shows the flowchart of frequency domain FWI we used.

\[
\omega^2 \rho u + \frac{\partial}{\partial x} [\lambda (\frac{\partial u}{\partial x} + \frac{\partial v}{\partial z}) + 2\mu (\frac{\partial u}{\partial x} + \frac{\partial u}{\partial z}) + \frac{\partial}{\partial z} [\mu (\frac{\partial v}{\partial z} + \frac{\partial u}{\partial z})] + f_x = 0
\]  

(1)

\[
\omega^2 \rho v + \frac{\partial}{\partial z} [\lambda (\frac{\partial u}{\partial x} + \frac{\partial v}{\partial z}) + 2\mu (\frac{\partial u}{\partial x} + \frac{\partial u}{\partial z}) + \frac{\partial}{\partial x} [\mu (\frac{\partial v}{\partial z} + \frac{\partial u}{\partial z})] + f_z = 0
\]  

(2)

\(\lambda\) and \(\mu\) are lame’s constants. \(\rho\) is density. \(\omega\) is circular frequency. \(f_x\) and \(f_z\) are the horizontal and vertical component of body force vector respectively. \(u\) and \(v\) are the horizontal and vertical component of displacement respectively.

![Figure 1 The flowchart of Frequency domain FWI](image)

---

82nd EAGE Conference & Exhibition 2020
8-11 June 2020, Amsterdam, The Netherlands
In FWI, the higher the frequency component is, the more likely the solution gets stuck to the local minimum and the more likely cycle skipping occurs (Viruex et al., 2009). When we conduct FWI in frequency domain, we could determine the order and total number of frequency components used in the inversion procedure. Therefore, by performing inversion process from low frequency components to high frequency components, those problem could be avoided (Pratt, 1999). For the gradient calculation, we use the parameterization by P- and S-wave velocity and density proposed by Mora (1987). As a preconditioning of gradient, we use a weighting based on the scattering theory (Teranishi et al., 2016). We use following scattering equations proposed by Wu and Aki (1985).

\[ \delta \rho, \delta \lambda, \text{ and } \delta \mu \text{ represent the heterogeneity of density and lame’s constants, respectively. } \]

\[ \rho_0, \lambda_0 \text{, and } \mu_0 \text{ are the back ground model of density and lame’s constants, respectively. } \]

\[ \text{Calculate the sensitivity of each parameter at each source-receiver configuration using equation (3), (4), (5), and (6), and correct the gradient.} \]

\[ \begin{align*}
ru^p &= \frac{\omega^2}{4\pi V_p^2} \frac{1}{r} e^{-i\omega(t-R)/\rho_0} \left\{ \frac{\delta \rho}{\rho_0} \cos \theta - \frac{\delta \lambda}{\lambda_0 + 2\mu_0} - \frac{2\delta\mu}{\lambda_0 + 2\mu_0} \cos^2 \theta \right\} \\
ru^s &= \frac{\omega^2}{4\pi V_p^2} \frac{1}{r} e^{-i\omega(t-R)/\rho_0} \left\{ \frac{\delta \rho}{\rho_0} \sin \theta + \left( \frac{V_s}{V_p} \right) \frac{\delta \mu}{\mu_0} \sin 2\theta \right\} \\
w^u &= \frac{\omega^2}{4\pi V_p^2} \frac{1}{r} e^{-i\omega(t-R)/\rho_0} \left\{ \frac{\delta \rho}{\rho_0} \sin \theta - \left( \frac{V_s}{V_p} \right) \frac{\delta \mu}{\mu_0} \cos 2\theta \sin \phi \right\} \\
's^u &= \frac{\omega^2}{4\pi V_p^2} \frac{1}{r} e^{-i\omega(t-R)/\rho_0} \left\{ \frac{\delta \rho}{\rho_0} \sin \theta + \left( \frac{V_s}{V_p} \right) \frac{\delta \mu}{\mu_0} \cos 2\theta \sin \phi \right\}
\end{align*} \] (3)

Model

We set a 2D subsurface model assuming the practice of foam-assisted EOR. Figure 2 shows the model. As we perform time-lapse monitoring simulation, we set another model, in which the foam zone of the model (figure 2) advanced 50 m towards the right-hand side of the model. Survey line is set at the top of the model. Survey line is 4000 m long. Seismic sources and receivers are located at the survey line with a constant offset of 400 m and 20 m, respectively. The total number of sources and receivers are 11 and 201, respectively. Physical properties of each zone are shown in Table 1. Properties of reservoir zone are calculated by Gassmann’s equation based on the properties shown in Table 2.

**Table 1 Physical parameters of each zone**

<table>
<thead>
<tr>
<th>zone</th>
<th>P-wave velocity [m/s]</th>
<th>S-wave velocity [m/s]</th>
<th>Density [g/cm³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shale 1</td>
<td>3300</td>
<td>1698</td>
<td>2.25</td>
</tr>
<tr>
<td>Shale 2</td>
<td>4300</td>
<td>2212</td>
<td>2.40</td>
</tr>
<tr>
<td>Water</td>
<td>4200</td>
<td>2521</td>
<td>2.40</td>
</tr>
<tr>
<td>Foam (Air)</td>
<td>4076</td>
<td>2572</td>
<td>2.30</td>
</tr>
<tr>
<td>Oil</td>
<td>4123</td>
<td>2533</td>
<td>2.37</td>
</tr>
</tbody>
</table>

**Figure 2 Water injection model. The middle layer is the reservoir (sand stone). The porosity of the reservoir is 0.15. Since foam is composed of gas bubbles, the pore spaces of reservoir rock at the foam front zone are assumed to be filled with air. Each zone of the reservoir is saturated with 70 % indicated fluids and 30 % water.**
Table 2 Properties of pore fluids

<table>
<thead>
<tr>
<th>Pore fluids</th>
<th>Density [g/cm$^3$]</th>
<th>Bulk modulus [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>0.9896</td>
<td>2.948</td>
</tr>
<tr>
<td>Oil</td>
<td>0.7706</td>
<td>0.989</td>
</tr>
<tr>
<td>Air</td>
<td>0.0943</td>
<td>0.0139</td>
</tr>
</tbody>
</table>

Results

In this study, we use five frequencies, 9 Hz, 14 Hz, 19 Hz, 24 Hz, and 29 Hz, for FWI. Figure 3 shows the variation of the misfit function at each iteration.

Figure 3 Misfit function. Misfit is normalized by the value of the first iteration of each frequency loop.

Figure 4 Vertical profile of each parameter. (a), (b), and (c) are the profiles obtained at left-hand side of the foam zone, and (d), (e), and (f) are the profiles obtained at right-hand side of the foam zone. Red, green and blue lines indicate the initial model (Before the advancement of foam zone), the true model (After the advancement of foam zone), and the inverted model, respectively.
Figure 5 Final correction amount. (a) P-wave velocity (b) S-wave velocity (c) density

Figure 5 shows the difference between initial and obtained structure of each parameter, in other words, the final correction amount of each parameter. Figure 4 is the vertical profile of each parameter which shows how the structure of parameters are recovered in the depth direction. From figure 4 and figure 5, we can see that structure of each parameter is well recovered by applying FWI. However, the density structure was not recovered very well comparing to the other parameters, P-wave velocity and S-wave velocity.

Conclusion

In the present study, we investigated the effectiveness of seismic methods to the monitoring of foam-assisted EOR and the feasibility of estimating property changes in the reservoir caused by the replacement of pore fluids using FWI. We conducted numerical experiments on the time-lapse monitoring of foam-assisted EOR. Our numerical experiments indicated that we could estimate the property changes of the reservoir and could capture the advancement of injected fluids quantitatively using FWI with preconditioning by scattering theory.

Reference


