Fundamental study for detecting subsurface foam advancement in the practice of foam-assisted EOR using RTM

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Recently, foam-assisted enhanced oil recovery (EOR) has drawn attention due to its effectiveness. However, the method to explore how the subsurface sweep foam front moves has not been fully studied yet. In the previous study, our numerical results indicated that subsurface foam distribution could be detected by seismic method with an amplitude versus offset (AVO) analysis. Since the effectiveness of the seismic method for capturing the location of foam front has been validated, our next step is to extend its applicability to monitor the movement of foam-saturated zone in a quantitative way. In this study, we conducted numerical experiments to examine the effectiveness of wave-theoretical seismic methods to time-lapse monitoring. We set 2D subsurface models supposing foam-assisted EOR with CO2 and water injection. We make synthetic data sets for these two models with different position of sweep foam front. We take the difference of waveforms between before and after the advancement of foam sweep front, and then, back propagate these residuals as sources. From the correlation of the forward and the backward wave fileds, we got the images of the vertical wave field which exaggerate the diffraction caused by the difference of position of foam sweep front. This result indicates that seismic exploration could detect the location of physical property change due to the advancement of sweep foam front in the practice of foam-assisted EOR.

1. INTRODUCTION

Recently, foam-assisted enhanced oil recovery (EOR) has drawn attention for its sweep efficiency and incremental oil recovery. Foam improves the efficiency of EOR by controlling the mobility of fluids. Although experimental and numerical studies related to foam-assisted EOR have been conducted[1)], the method to explore the subsurface sweep foam front has not been established yet. It is certainly important to see how the sweep foam front advances towards the production well. Therefore, to monitor the movement of foam front could be an essential tool for improving the efficiency of oil production.

In our previous study[2)], our numerical results indicated that the distribution of subsurface foam could be detected by amplitude versus offset (AVO) analysis The feasibility of the seismic method, therefore, has been validated on capturing foam front, and the applicability in the locationing of the front in the subsurface needs to be investigated as a second step. Since the change in the acquired waveforms has been confirmed by the AVO analysis, the difference in the waveform could be utilized in the locationing as suggested in the method of full waveform inversion[3)].

In this study, we investigate the effectiveness of the seismic survey to the time-lapse monitoring of foam front. We hypothesized that reverse time migration (RTM)[4)] could capture the movement of sweep foam front in the subsurface. To validate this hypothesis, we conducted numerical experiments using finite-difference method. We make synthetic data sets for the models before and after the advancement of sweep foam front. Then, we apply RTM to the data sets. We investigate the potential of seismic method to monitor the advancement of sweep foam front in the practice of foam-assisted EOR.

2. METHOD

We discretized stress-strain relationship and equation of motion by the finite-difference method with the staggered grit[5)] and propagate elastic wave using numerical models. We apply RTM to obtained data set. We take the difference of waveforms for shot gathers before and after the advancement of sweep foam front, and then, back propagate the residuals as sources from each receiver point. By taking the correlation of forward and backward wave fields for each shot gather and summing up them, we make subsurface model image which exaggerate the part where the residuals were generated. The flow of RTM we use is as shown in figure 1.

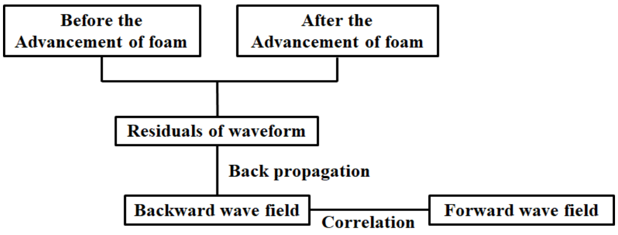

Figure 1 Flowchart of RTM

3. MODEL

We use four types of numerical models. Two of them are possible conditions in foam-assisted EOR, i.e. CO_2 injection as shown in Figure 2 and water injection as shown in Figure 3. We assume that pore spaces of reservoir rock (middle layer in the figure) at the foam front are filled by air. In the other two models, this foam front advanced 50 m from model1 and model2 towards the production well (right hand side of the models). Seismic sources and receivers are located at the survey line with a constant offset of 400 m and 20 m, respectively, i.e. 9 sources and 161 receivers. Physical parameters for each layer are shown in Table 1. These parameters are calculated by the Gassmann's equation using the fluid properties as shown in Table 2. Porosity of the reservoir layer is set to 0.2.

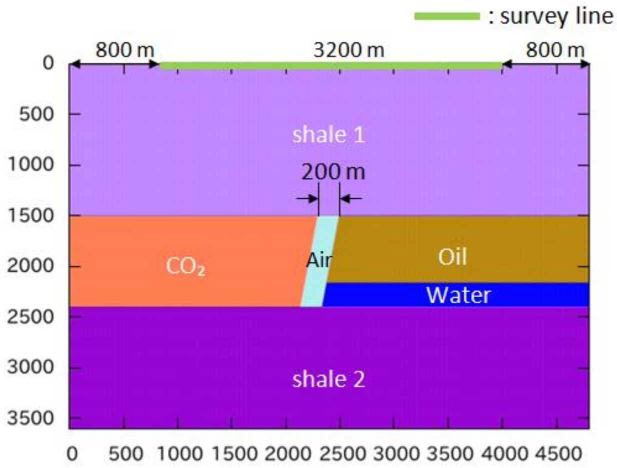

Figure 2 Model1 CO_2 injection

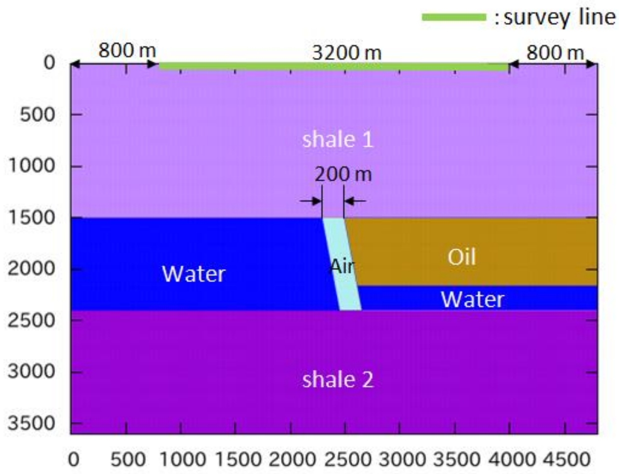

Figure 3 Model2 Water injection

Table1 Parameter of each layer

	Vp [m/s]	Vs [m/s]	ρ [g/cm³]	λ [GPa]	μ [GPa]
Shale1	3300	1698	2.250	20.50	11.48
Shale2	4300	2212	2.400	32.89	18.55
CO_2 (supercritical)	4035	2578	2.248	6.72	14.94
Water	4091	2538	2.318	14.94	14.94
Oil	4075	2554	2.290	8.15	14.94
Air (Foam)	4139	2655	2.118	6.42	14.94

Table2 Properties of fluids in the pore of reservoir

	CO_2 (supercritical)	Water	Oil	Air (Foam)
Bulk Modulus [GPa]	0.25	2.25	1.5	1.38×10^{-4}
Density [g/cm³]	0.65	1.0	0.86	1.091×10^{-3}

4. RESULT

First, we take the difference between waveforms for each shot gather before and after the advancement of sweep foam front. **Figure 3** is the residual of shot gather, the source is at the center of survey line of Model1 (**Figure 2**).

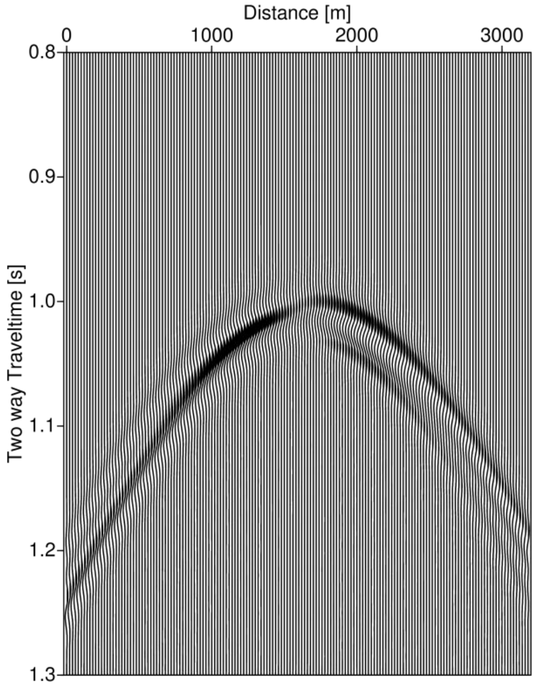

Figure 3 Residual of waveform Vz (Model1)

Then, we back propagate these residuals as sources from receiver positions. We take the correlation of obtained backward wave field with forward wave field for each shot gather and sum up the results. **Figure 4** and **Figure 5** are the final results obtained by RTM. In these figures, transverse axis corresponds to the survey line of the models and vertical axis is depth whose range is from surface (top of the models) to the bottom of the reservoir. We can see the strong signal at the center of models with the depth of 1500 m. Before the advancement of foam (Air), the foam (Air) layer ranges from 2300 m to 2500 m, and after the advancement of foam, it ranges from 2350 m to 2550 m. From the above, we can find that the position of strong signal in **Figure 4** and **Figure 5** shows where the residuals were generated, in other words, where the sweep foam front moved. The strong signal in each figure consists of two portions, left hand side and right hand side. In **Figure 4**, the signal of left hand side is induced by the replacement of CO2 to foam, right hand side is induced by the replacement of oil to foam. In **Figure 5**, the signal of left hand side is induced by the replacement of water to foam, right hand side is the same as **Figure 4**. From the strength of the signal, the detection for advancement of subsurface foam is easier in the case of water injection than in the case of CO2 injection

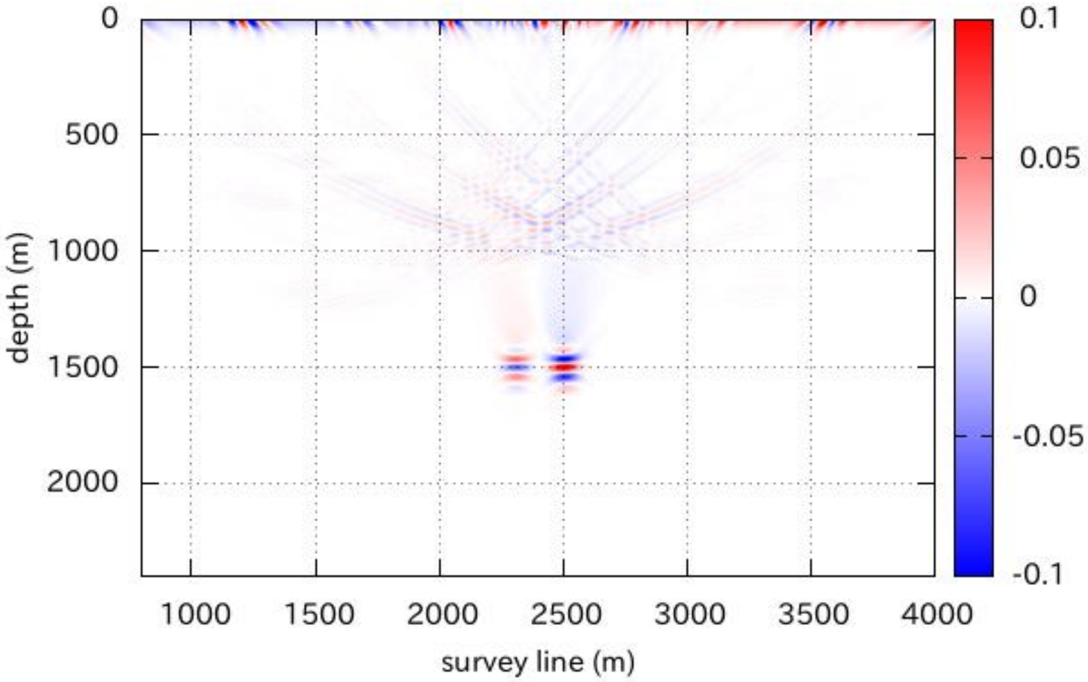

Figure 4 Model1 RTM image

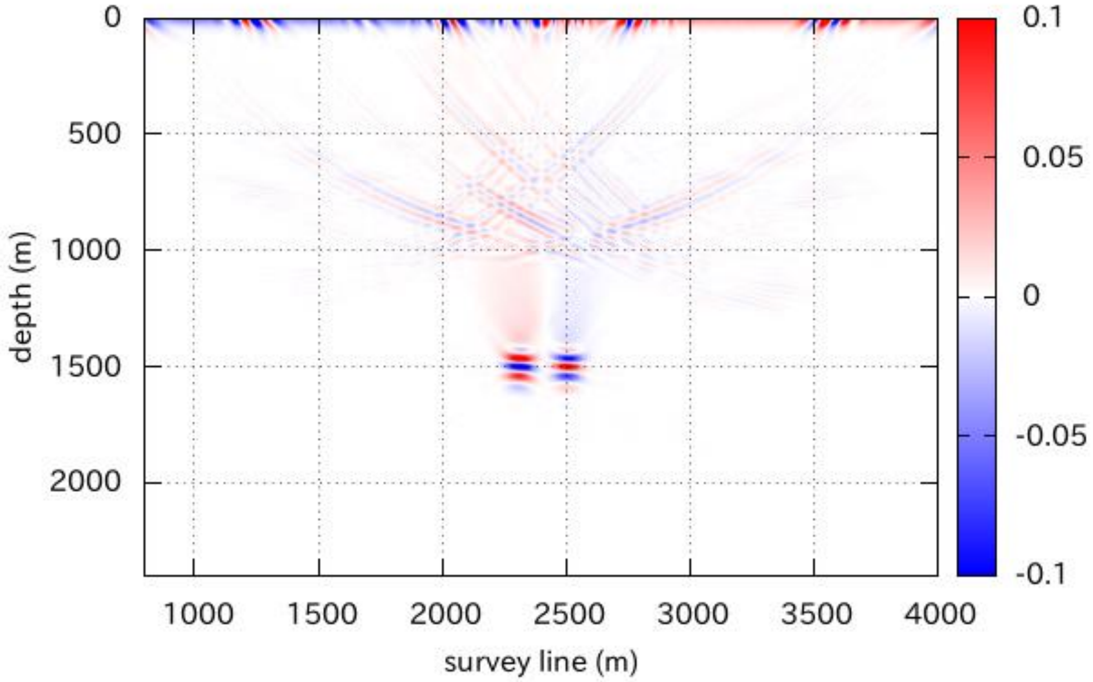

Figure 5 Model2 RTM image

5. CONCLUSION

In the present study, we examine the feasibility of seismic monitoring of foam-assisted EOR by numerical experiments. We use the RTM to monitor the advancement of subsurface sweep foam front. We make shot gathers from synthetic data generated by numerical simulation for CO2 injection and water injection models. We calculate the difference between waveforms for each shot gather before and after the advancement of sweep foam front, and back propagate the residuals to calculate backward wave field. And then, we take correlation of forward wave field and backward wave field. The obtained images clearly show the location of the movement of foam front. In the present study, we only use the vertical component of the received data for imaging the subsurface. So we need to image the subsurface including the horizontal component in our future work. We will apply the present method to more complicated models, e.g. the model which has transition areas at the boundary between foam layer and the layer of other fluids. This study could be a first step leading to the full-waveform approach which would show the more detailed information on the movement of subsurface sweep foam front.

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