Microseismic analysis for kinematic parameters of subsurface permeable flow

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In recent years, a method called passive Seismic Emission Tomography (SET) attracts attention in the petroleum industry. SET estimates the subsurface areas of fluid flow where the seismic noise could be generated due to minor pressure fluctuations caused by the flow in the reservoir using seismic data. In this study, we hypothesized that micro seismic waves used in SET contain fluid flow information such as fluid properties, flow channels, or what the phases are immixed in the flow. We tested, with numerical experiments, if the frequency of seismic signals we observe in the application of SET reflects the fluid rate, i.e., a parameter defined by fluid viscosity, differential pressure and a channel shape. In numerical experiments, we simulate the two-phase flow of water-oil flowing through the channel of a pore throat with a narrow segment to see what the frequency of seismic signals generated at the wall of the channel by using the lattice Boltzmann method in a 3D space. Our numerical experiments found that seismic waves of 10 - 30 Hz would be generated when a droplet passes through the pore throat. The seismic frequency depends on the length of the narrow segment and the flow rate. Since it is known that the location of seismic emission could be estimated in the range of resolution defined by seismic observation, our results indicate the possibility to estimate the flow-related parameters as a function of space. We would like to conclude: i) seismic waves observed in SET are generated by the fluid flow ii) observed seismic frequency includes a characteristic parameter defined by the length of narrow segment and the flow velocity.

1. INTRODUCTION

Recently, a method called passive Seismic Emission Tomography (SET) has been tried to observe seismic waves caused by fluid flow in a crack and grasps the crack distribution in reservoir [1,2]. However, researches for practical application of the methods have been dominant, and theoretical development focusing on seismic wave generation due to fluid flow has not been actively conducted. Since the generation of seismic waves due to fluid flow and the location identification of such seismic waves have been confirmed[3,4], it is necessary to confirm how much extent we could exploit the advantages of the method.

As microseismic waves generated by fluid flow contains waves in the seismic band, i.e., 10-30 Hz, the generation of waves should be related to kinetic phenomena. The phenomena we are looking at for SET is the passage of a droplet through a narrow segment of the pore throat, and the seismic waveform might contain information on the fluid motion (ex: viscosity, velocity) and the dimension of the pore throat causing pressure disturbance (ex: width, length). We could therefore start discussing this fluid motion in terms of the seismic emission.

In this study, we calculate the stress disturbance along the wall of the pore throat due to fluid flow in which a water droplet is immixed in crude oil. The droplet causes time-variant stress disturbance at the wall to induce seismic waves. As a numerical analysis method, we adopt a lattice Boltzmann method because of the simplicity to set up the boundary condition and to introduce parallel computation. We assume a pipe-shape fuid path in which the narrow segment is located as a pore throat. We calculate pressure disturbance along the wall and integrate them in time and space to estimate the seismic emission. We changed the parameter of fluid and shape of throat in each simulation. We use running spectra derived from those seismic waves to directly identify the synchrony between the frequency of emitted seismic waves and the behavior of the droplet. From these results, we discuss the possibility of estimating information such as flow velocity and channel shape.

2. MODEL

In this study, we simulate two-phase fluid flows in the pore throat of a fluid path depicted in Fig.1. We set the initial condition for a water droplet in the center of the flow and 6.02 mm (70 grid) away from the left boundary. The fluid with the droplet starts flowing for more than 3000 steps in space in the simulation, and after that it was fixed to the average

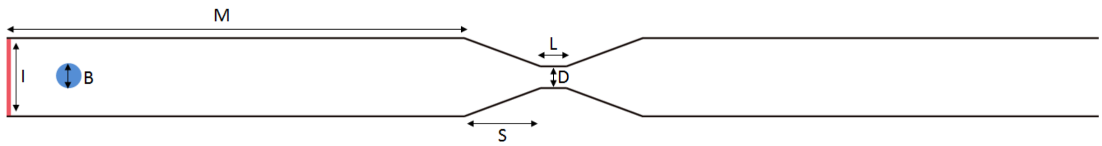

Figure 1 Pore throat model used in this study

flow rate of 0.172 m/s. Other parameters are shown in Table 1.

For simulating the frequency contents of the emitted seismic waves, we use the wave theory. For a given displacement potential $\phi(\vec{r},t)$ at the location $\vec{r}$ and time t satisfies the following Helmholtz equation.

$$\left(\frac{1}{c}\right)^2\left(\frac{\partial}{\partial t}\right)^2\phi(\vec{r},t)=\nabla^2\phi(\vec{r},t)+f(\vec{r},t) \qquad (1)$$

where c is the seismic phase velocity and $f(\vec{r},t)$ is the source term. Based on the wave theory, the frequency contents of the solution $\phi(\vec{r},t)$ depends on $f(\vec{r},t)$ in the case of the forced oscillation. Therefore, we need to simulate $f(\vec{r},t)$ to see what the seismic frequency would be generated when fluid moves in the model shown in Fig. 1. We also investigated whether the seismic frequency depend on the internal fluid properties and the flow channel shape or not.

Table 1 Parameters

M	0.1376	[m]
L	2.75	[mm]
B	1.72	[mm]
S	5.16	[mm]
D	1.892	[mm]
I	4.042	[mm]
Density (oil)	1323	[kg/m^3]
Density (water)	1000	[kg/m^3]
Surfer tension	14	[dyne/cm]
Viscosity (oil)	1.5×10^{-5}	[m^2/s]
Viscosity (water)	1×10^{-6}	[m^2/s]
velocity	0.172	[m/s]
Δx	8.6×10^{-5}	[m]
Δt	1×10^{-5}	[s]

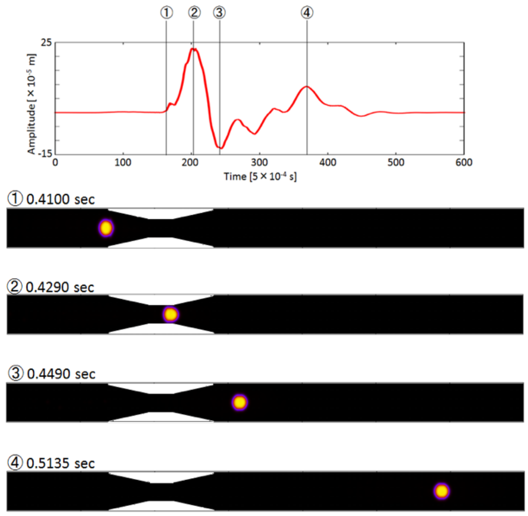

Figure 2 seismic wave and position of droplet

3. RESULT

We show the positions of the droplet and the corresponding steps in time as shown in Fig.2. In the figure, the segment of the flow path from 0.1204 m to 0.1806 m (1400 grid to 2100 grid) is displayed. For the time series displayed in Fig. 2, we show the running spectra in a variable density plot as shown in Fig.3. We use the sliding time window of 0.05 sec width at every moment in time, for which the maximum entropy method was used to estimate the spectra. The running spectrum shown in Fig. 3 is normalized at the maximum values of spectrum at each time step. For the time from 100 to 300 msec (time step from 200 to 600) in Fig.3, there is a series of amplitude fluctuation or wavetrains. However, we

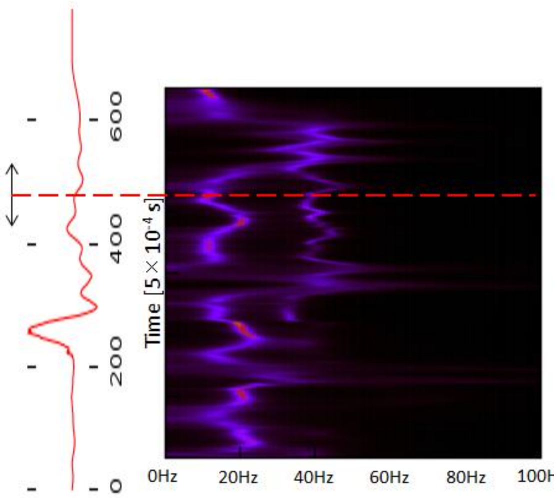

Figure 3 Running spectrum

Table 2 Parameters

L	1.03~8.77	[mm]
S	0.516~1.89	[mm]
Density (oil)	970~1499	[kg/m^3]
Surface tension	14~26	[dyne/cm]
Velocity	0.129~0.2	[m/s]

see only a half of the wavetrains is related to the motion of the droplet passing through the pore throat, since the wavetrains in the other part were found artificial in the simulation such as pressure reflection from the left boundary, etc. In this study, we therefore focused on the first half of the seismic wave. Fig. 3 also tells us that the generated seismic waves have frequencies around 20 Hz at the peak amplitude of the seismic trace.

We then investigated the dependency of the frequency contents against the internal fluid properties and the flow channel shape. The changed parameter and changing range are as shown in Table 2, and the parameters not shown in Table 2 are in the same as Table 1. In addition, each seismic waveform

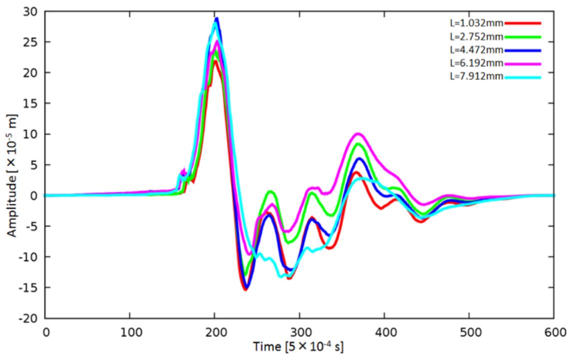

Figure 4 observed waveform against variation in parameter L.

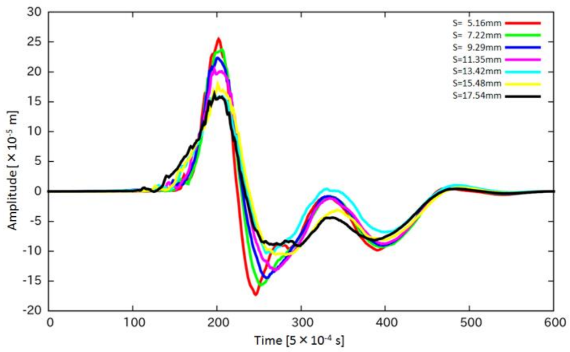

Figure 5 observed waveform against variation in parameter S.

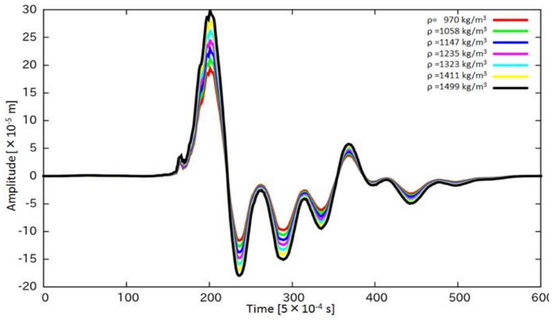

Figure 6 observed waveform against variation in oil density.

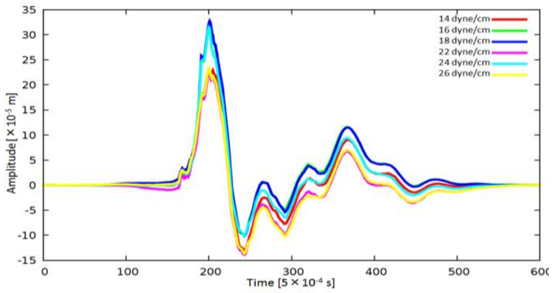

Figure 7 observed waveform against variation in surface tension of the droplet.

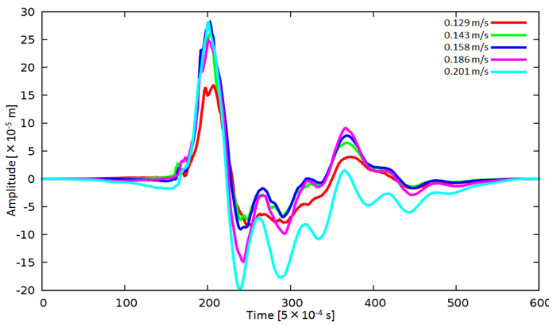

Figure 8 observed waveform against variation in sound velocity.

is shifted in time to have the amplitude peak to come at 0.1 sec. in the time axis. Figures 4-8 depict the variations in the waveform against each of the parameters in Table 2.

From those results, we conclude that only the lengths of S, L and the average flow velocity could influence the frequency spectra for seismic wave. Since seismic waves are generated by the droplet passage, the cycle of the elastic waves can be expressed by the time length T which means the droplet passing time. The transit time T of the droplet can be inferred to be

$$T = \frac{2S + L}{V_{ave}} \qquad (2)$$

using the lengths S and L and the average flow velocity V_{ave}. The frequency of the seismic wave is

$$F = 2 \times \frac{V_{ave}}{2S + L} \quad (3)$$

because the seismic wave is generated by the half cycle of passing droplet. We simulate the seismic waveforms for the combination of the parameters S, L and V_{ave} shown in Table 3. We estimate the running spectra to find the peak frequency for the estimated, and calculated the peak frequency expected from Eq.(3) (obtained) as shown in Fig. 9.

Table 3 Parameters for the observation of peak frequency of generated waveforms.

No.	S	L	V
1	5.16 mm	2.752 mm	0.172 m/s
2	7.224 mm	3.096 mm	0.172 m/s
3	9.288 mm	3.44 mm	0.172 m/s
4	11.352 mm	3.784 mm	0.172 m/s
5	13.416 mm	4.128 mm	0.172 m/s
6	15.48 mm	4.472 mm	0.172 m/s
7	17.544 mm	4.816 mm	0.172 m/s
8	5.16 mm	1.032 mm	0.172 m/s
9	5.16 mm	1.892 mm	0.172 m/s
10	5.16 mm	2.752 mm	0.172 m/s
11	5.16 mm	3.612 mm	0.172 m/s
12	5.16 mm	4.472 mm	0.172 m/s
13	5.16 mm	5.332 mm	0.172 m/s
14	5.16 mm	6.192 mm	0.172 m/s
15	5.16 mm	7.052 mm	0.172 m/s
16	5.16 mm	7.912 mm	0.172 m/s
17	5.16 mm	8.772 mm	0.172 m/s
18	5.16 mm	4.816 mm	0.172 m/s
19	7.224 mm	4.816 mm	0.172 m/s
20	9.288 mm	4.816 mm	0.172 m/s
21	11.352 mm	4.816 mm	0.172 m/s
22	13.416 mm	4.816 mm	0.172 m/s
23	15.48 mm	4.816 mm	0.172 m/s
24	17.544 mm	4.816 mm	0.172 m/s
25	5.16 mm	2.752 mm	0.129 m/s
26	5.16 mm	2.752 mm	0.14333 m/s
27	5.16 mm	2.752 mm	0.15767 m/s
28	5.16 mm	2.752 mm	0.172 m/s
29	5.16 mm	2.752 mm	0.18633 m/s
30	5.16 mm	2.752 mm	0.20067 m/s

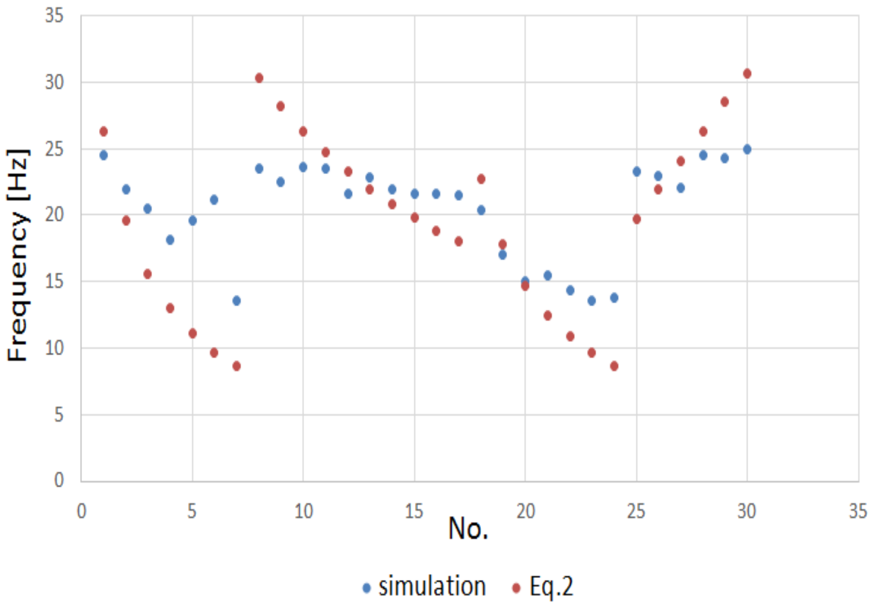

Figure 9 Comparing the estimated (red dots) and the calculated (blue dots) frequency peaks.

As shown in Fig.9, the two trends are mostly consistent and proves that the peak frequency of seismic waveforms is defined by the length of pore throat and the flow velocity.

4. CONCLUSION

In this study, assuming the oil production situation, we calculate the pressure disturbance observed on the wall of the flow path of crude oil immixed with a water droplet. We simulate seismic waveform generated by the pressure fluctuation for various model parameters, i.e. fluid properties and shape of the flow channel. Our running spectrum analysis found that the peak frequencies of seismic waveforms range 10 - 30 Hz when the droplet passes through the pore throat. The frequency band generated by the combination of the throat length and the flow velocity is the same as that of the seismic wave. Our results indicate, i) the seismic waves observed in SET is caused by the pressure fluctuations due to fluid flow, and ii) the peak frequency is defined by the flow path shape and velocity.

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