Utilization of seismic attenuation in the monitoring of CO\textsubscript{2} geological storage project

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Abstract

Aiming quantitative monitoring of subsurface in CO\textsubscript{2} geological storage project, this paper presents relationship between seismic attenuation and CO\textsubscript{2} saturation. The relationship enables more reliable quantitative monitoring, because seismic attenuation becomes available for estimating amount of CO\textsubscript{2} in addition to seismic velocity. We introduce theoretical relationship which is built with patchy saturation model and standard linear solid model. In order to validate the models and the methodology, we compare the predicted attenuation with an experimental dataset. The result shows good agreement; therefore the methodology is considered to be appropriate to establish the relationship between seismic attenuation and CO\textsubscript{2} saturation.

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1. Introduction

The monitoring of subsurface CO\textsubscript{2} migration and distribution is of great importance for assessment of the safety in the CO\textsubscript{2} geological storage project. In addition, quantitative estimation of amount of CO\textsubscript{2} in underground will be required for the expected and advanced role of the monitoring in the future, e.g., for the CO\textsubscript{2} emissions trading system.

Among many monitoring techniques, seismic methods have been selected as the most reliable method in many worldwide CO\textsubscript{2} geological storage projects. Seismic reflection method has contributed to delineate the subsurface
CO₂ distribution in many sites. Seismic tomography has been useful to identify the location by finer scale. Sonic logging has been conducted as a detailed monitoring technique near the borehole.

In the seismic methods, the velocity has been mainly used for the monitoring purpose. However, the attenuation of seismic waves has not been utilized for the CO₂ monitoring since the accurate measurement of amplitude is difficult due to the requirement of high signal to noise ratio on the field surveying. Moreover, the quantitative relationship between the attenuation of seismic wave and CO₂ saturation has not been investigated sufficiently in the past. Therefore, if the accurate relationship is established, the estimation of amount of underground CO₂ by seismic method will become much more reliable and the utilization of seismic methods will be expanded.

At Nagaoka, Japan, we found that injected CO₂ was distributed partially in pore space of reservoir rock by analyzing sonic logging data [1]. This distributed state is called a “patchy saturation” [2]. The patchy saturation is caused by the fact that CO₂ cannot invade into the small sized pores due to the capillary pressure, when replacing water with CO₂ in pore space, in other words, “drainage process”. Hence, the injected CO₂ does not distribute uniformly. In order to deal with the seismic attenuation due to CO₂ injection, we need to establish a formula of the seismic attenuation at the patchy saturation case.

In this paper, we seek to present a reliable relationship between seismic attenuation and CO₂ saturation for the quantitative monitoring. Theoretical relationship is derived from the patchy saturation model and the standard linear solid model. In order to validate the relationship, we apply the methodology to existing experimental dataset.

2. Model and Methodology

2.1. Patchy saturation model

It is widely recognized that effective bulk modulus of rock is different between the patchy saturation and uniform saturation. Uniform saturation means that all pores are occupied by mixed fluid with a constant saturation. In this case, the effective bulk modulus is calculated by Gassmann’s equation and Woods equation [2].

\[
\frac{K_{sat}}{K_o - K_{sat}} = \frac{K_{dry}}{K_o - K_{dry}} + \frac{K_{fl}}{\phi(K_o - K_{fl})} \\
\frac{1}{K_{fl}} = \frac{S_g}{K_g} + \frac{S_w}{K_w}
\]  

(1)  

where \( K_{sat} \) is the effective bulk modulus of rock, \( K_o \) is the bulk modulus of mineral, \( K_{dry} \) is the bulk modulus of dry frame, \( K_{fl} \) is the bulk modulus of pore fluid, \( \phi \) is porosity, \( S_g \), \( S_w \) are volume fraction of pore space occupied with gas and water respectively. This model is called Gassmann-wood model [2].

On the other hand, in the case of patchy saturation, the effective bulk modulus is calculated by harmonic average of P-wave modulus for fully water saturated and fully gas saturated rock [3].

\[
\frac{1}{M_{eff}} = \frac{V_w}{M_w} + \frac{V_g}{M_g}
\]  

(3)  

\[
M = \rho V_p^2
\]  

(4)

, where \( M_{eff} \) is the effective P-wave modulus of the rock, \( V_w \) is the volume fraction of water in the pore space, \( M_w \) is the P-wave modulus of water saturated rock, \( V_g \) is the volume fraction of gas and \( M_g \) is the P-wave modulus of gas saturated rock. Both \( M_w \) and \( M_g \) are calculated by Gassmann’s equation. \( \rho \) is density and \( V_p \) is P-wave velocity. This model is called Gassmann-Hill model.

In the above mentioned patchy saturation, it is assumed that the some pores are fully saturated by CO₂. However, this assumption is hard to accept since usually irreducible water exits in small pores. Hence the modified
patchy saturation model was introduced [1]. This idea corresponds to an existing of maximum CO₂ containable pore volume [1], or irreducible water saturation, which is a parameter used in the two phase flow simulation [4]. We named the maximum CO₂ containable pore volume fraction critical gas saturation. In the modified patchy saturation, the effective P-wave modulus can be calculated by replacing P-wave modulus of gas part to P-wave modulus filled with critical gas saturation in eq. (3). The formula of the eq is asfollows.

$$\frac{1}{M_{\text{eff}}} = \frac{V_w}{M_w} + \frac{V_g}{M_{cg}}$$  \hspace{1cm} (5)

, where $M_{cg}$ is P-wave modulus of gas saturated part in the critical gas saturation.

Fig. 1 illustrates a relationship between P-wave velocity and CO₂ saturation together with schematic diagram corresponding to the three different models; uniform, standard patchy, and modified patchy. The theoretical line of the modified patchy saturation model falls between the uniform and the standard patchy saturation lines.

Fig.1. Schematic diagram explaining several saturation models [1]

Azuma et al., [1] applied these models to logging data obtained in Nagaoka, which is the first pilot project of CO₂ geological storage to saline aquifer in Japan. P-wave velocity is obtained by sonic logging. CO₂ saturation is obtained by neutron logging. The comparison between the model prediction and logging data is shown in Fig.2. This figure shows good agreement between the modified patchy model and logging data, and this result indicates that the pore space are not uniformly saturated but partially saturated by CO₂.

Fig.2. Result of comparison between the prediction by models and logging data [1]
2.2. Seismic attenuation in patchy saturation

Several studies regarding seismic attenuation and dispersion associated with wave-induced fluid flow, which is pore fluid flow induced by seismic wave are summarized by Muller et al. [5]. According to Muller et al. [5], different kinds of models and theories exist to explain the various mechanisms depending on the scale.

Among those models, we adopt the standard linear solid model (SLS) [2], which is based on a behavior of viscoelastic material. So far, the model has contributed to understanding of the attenuation and dispersion of the patchy saturation [6] [7]. This linear solid model describes a response of a linear combination of springs and dashpots to represent elastic and viscous components, respectively. Schematic diagram is shown in Fig.3.

![Fig.3. Schematic diagram of standard linear solid model [2]](image)

Assuming the standard linear solid model, we can obtain the attenuation and elastic modulus as a function of frequency by Kramers-Kronig equation [2] (Fig.4). This equation links the attenuation and the frequency dependent modulus (dispersion), so the attenuation can be calculated from elastic modulus and critical frequency.

\[
\frac{1}{Q} = \frac{M_\infty - M_0}{\sqrt{M_\infty M_0}} \frac{f / f_c}{1 + (f / f_c)^2}
\]

(6)

where \(Q\) is attenuation factor, \(M_\infty\) is elastic modulus at high frequency, \(M_0\) is elastic modulus at low frequency, \(f_c\) is critical frequency and \(f\) is applied seismic frequency. The critical frequency means transition frequency from low frequency to high frequency regions, and we use the critical frequency to discriminate the uniform saturation from the patchy saturation in our model. The critical frequency for patchy saturation model is described in eq. (7) [2]

\[
f_{patchy} \approx \frac{\kappa K_f}{L^2 \phi \eta}
\]

(7)

where \(\kappa\) is permeability of rock, \(K_f\) is the bulk modulus of fluid in pore space, \(L\) is patch size, \(\phi\) is porosity, \(\eta\) is
viscosity of the fluid.

3. Applying the model to laboratory dataset


A series of laboratory dataset of seismic velocity and attenuation at different water saturation is available in Cadret et al., 1995, 1998 [8], [9]. The rock specimen was limestone, and measurement method was resonant-bar method. The porosity of the specimen was 30% and the permeability was 255 mDarcy. These data were measured in patchy and uniform saturation state. These saturation states were realized by drying and depressurization of rock-sample in pressurization tank. By drying process the patchy saturation state was realized, and by depressurization process the uniform saturation state was realized. These saturation states are confirmed with X-ray CT images (Fig. 5.). The white parts in the image indicate pores occupied with air. This image convinces us that the drying and depressurization processes cause the different saturation states clearly.

![Fig.5. X-ray CT images at drying (patchy) and depressurization (uniform) state [8]](image)

Seismic velocity versus water saturation measured in this experiment is shown in Fig. 6. The white circles denote data measured in drying state which corresponds to the patchy saturation. The black circles denote data measured in depressurization state which corresponds to the uniform saturation. From this figure, we found that the velocities in the patchy saturation are always larger than in the uniform saturation at all saturation. This tendency is consistent with the model and the methodology described above.

![Fig.6. Extensional velocity vs. water saturation obtained with drying-state and depressurization -state [8]](image)
Measured seismic velocity by the resonant bar method is an extensional velocity. This velocity links to P-wave velocity and S-wave velocity as shown in eq. (8).

\[ V_e^2 = \frac{3V_p^2 - 4V_s^2}{V_p^2 - V_s^2} \]  

(8)

where \( V_e \) is the extensional velocity. \( V_p \) is P-wave velocity. \( V_s \) is S-wave velocity. And Young modulus and extensional velocity is connected by eq. (9). Here, \( \rho \) is density.

\[ E = \rho V_e^2 \]  

(9)

Fig. 7 shows measured seismic attenuation with water saturation. These data were measured with drying stage and depressurization stage. Only seismic attenuation (Qe) at drying stage which corresponds to patchy saturation state has a large variation in the data. S-wave doesn’t depend on fluid in pore space. At uniform saturation state, attenuation hardly occurs by wave induced fluid flow. In the patchy saturation state, seismic attenuation takes maximum value at large water saturation, about 0.98 as shown in Fig. 7.

![Fig. 7. Seismic attenuation vs. Water saturation obtained with drying-stage and depressurization-stage [9]](image)

3.2. Comparison of model prediction and observation

We calculate attenuation with the standard solid model from seismic velocity using eq. (6). For this calculation, we need to determine the critical frequency. As shown in eq. (7), most of necessary parameters for the calculation can be easily determined except patch size. Here, we determined the patch size from X-ray CT image (Fig. 5).

Our used values of these parameters are as follows. The permeability and porosity give 255 md, 30% respectively from Cadret et al., [8]. Fluid viscosity and bulk modulus give parameters of water, 0.0001Pas and 2.5GPa, respectively and the patchy size is 0.03, 0.04m. In Fig. 8, we compare the attenuation calculated with the model to data measured in the laboratory. As shown in this figure, we achieve good agreement with calculation result based on the model and experimental dataset; thus the standard linear solid mode and the calculation methodology are appropriate to predict relation between the attenuation and the water saturation.
As noted above, at Nagaoka, seismic velocity can be described with the patchy saturation model by analyzing the logging data. We predict variation of seismic attenuation with CO\textsubscript{2} saturation by the standard solid model and the proposed calculation method. The calculation result is shown in Fig.9. Seismic attenuation takes maximum value at small CO\textsubscript{2} saturation, about 8\%. At Nagaoka, sonic logging data has been measured for reading of correct first arrival time with variable and non-recordable amplifier gain. Accordingly, the sonic log apparatus does not preserve amplitude; thus, we were not able to compare the predicted attenuation with measured one.

4. Summary and new application

Aiming more reliable quantification of monitoring at CO\textsubscript{2} geological storage project, we presented the relationship between seismic attenuation and CO\textsubscript{2} saturation. In theoretical introduction, we adopted the patchy saturation model and the standard linear solid model for calculating of the attenuation regarding rock whose pore spaces are occupied with CO\textsubscript{2} and water.

In order to validate these models and the methodology, we applied them to an existing laboratory-experimental dataset. The comparison of model prediction with the dataset showed that the models and the methodology were appropriate to establish the relationship.
As an application of the above the model and methodology, we predicted the seismic attenuation from sonic logging at Nagaoka. The result indicates that the maximum seismic attenuation occurred on small CO₂ saturation, 10%.

A phenomenon that the maximum attenuation occurs on small CO₂ saturation at patchy saturation can be seen in some other literatures [6], [7], [10]. This phenomenon suggests a big advantage for the monitoring of the CO₂ leakage from the storage layer. That is because, it enables us to detect CO₂ leakage in the earlier stage for the reason that a small amount of leaked CO₂ can be caught by observing the change of the seismic attenuation.

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