Influence of water saturation on ultrasonic P-wave velocity in weakly compacted sandstone

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Abstract. Laboratory measurements of Ultrasonic P-wave velocities were conducted in weakly compacted sandstone with varying degree of water saturations. We used P wave transducer at frequency 63 kHz and imbibition technique in order to study the influence of water saturation on the P-wave velocity. Our experiment showed that the P-wave velocity (Vp) was reduced significantly at the beginning of the imbibition process. The variations on travel times and the amplitude changes were detected at any degree of saturation. The first and second amplitude of P wave decreased as water saturation (Sw) increased in the range of 0.1 to 0.6 in B5 sample, the amplitude increased again afterward. The shifting peaks of the signal that indicated attenuation were also observed in the experimental.

1. Introduction

Accurate estimation of fluid saturation in oil reservoir requires a good understanding of the relationship between seismic signal and fluid saturation in porous medium. There are various types of rocks that make up oil reservoirs, one of which is weakly compacted sandstone. In this paper, the influence of fluid saturation of seismic signal has been investigated using water imbibition experiments in the Ngrayong sandstone. Ngrayong sandstone, which is clean quartzose sandstone, is taken from the outcrop of Ngrayong formation in Blora, Central Java [1]. Previous studies have reported the relation of velocity-saturation in the consolidated medium[2-5], and unconsolidated sand[6]. Changes of velocity due to saturation are complicated and depend on many parameters, such as poroelastic parameters and position of the patch in the rock [7][8]. There are two theoretical bounds to explain the relation of velocity-saturation [9][10]. In the low frequency limit, rock bulk modulus and fluid bulk modulus are defined by the Gassmann-Wood equation and for the high frequency limit is defined by the Gassmann-Hill equation.

In order to get a deeper understanding of the influence of water saturation to the wave signal in rock reservoir, we use weakly compacted sandstone. Water saturation can be obtained by using the
Imbibition technique in the laboratory. Imbibition is the process of replacing non-wetting fluid with wetting fluid, followed by depressurization of a saturated sample in a porous medium [2][7].

2. Laboratory Experiments
The Experiments were conducted on four cylindrical samples of Ngrayong sandstones. Rock samples were dried in oven at 120 °C for 48 hours. Then, porosity values were measured from all samples using porosimeter. After the Rock properties of each sample were known (Table 1), imbibition process was performed on the variations of saturation degree. Imbibition was conducted by dropping water on the surface of rock samples with a volume of water according to the degree of saturation and rotated to make water distributed homogeneously in rock samples.

| Parameter        | B2     | B3     | B5     | B7     |
|------------------|--------|--------|--------|--------|
| Porosity (%)     | 37.45  | 37.55  | 38     | 37.5   |
| Bulk Density (g/cm³) | 2.06   | 2.44   | 2.57   | 2.1    |
| Diameter (cm)    | 3.82   | 3.86   | 3.92   | 3.9    |
| Length (cm)      | 4.29   | 4.2    | 2.95   | 3.7    |
| Bulk Volum (cc)  | 39     | 32     | 22     | 39     |
| Pore Volum (cc)  | 14.61  | 12.16  | 8.56   | 14.65  |
| Mass (gr)        | 82.14  | 78.04  | 56.3   | 71.53  |

P-wave velocity measurements were accomplished using OYO sonic viewer model 5210 at frequency of 63 kHz in a direction parallel to the core axis. The output of ultrasonic waves was displayed on a digital oscilloscope (Tektronix TDS 2022C). Then the data and image could be stored in particular format. When mechanical impulses generated by the pulse of generator propagates along rock samples with length L (meter), and the travel time of pulse T (second), P wave velocity (V) of the propagating wave can be calculated by:

\[ V = \frac{L}{t} \]  

The errors obtained for travel time and sample height determination were < 3% and <1%, respectively, while for relative velocity value, <9%. Table 2 shows the XRF and SEM investigations of rock samples that mainly composed of silicon (Si), iron (Fe), and potassium (K). Silicon is present in the form of SiO₂, indicated quartz as the major constituent of sandstone. Ferrous iron is the constituent of smectite (nontronite) group, while the main constituents of clay minerals group are chlorite, biotite, carbonate (siderite, ankerite) and sulfide. Smectite clays may inflate when they contact with liquid [11].

| XRF mineral | Percentage (%) | SEM and EDS (mineral and compound) |
|-------------|----------------|-----------------------------------|
| Si          | 56.1           | Quartz                           |
| K           | 6.52           | Fe                                |
| Ca          | 3.54           | Ti                                |
| Ti          | 2.77           | Ca                                |
| V           | 0.09           | K                                 |
| Cr          | 0.11           | Si                                |
| Mn          | 0.29           | Al                                |
| Fe          | 30.3           | Mg                                |
| Ni          | 0.12           | Na                                |
| Cu          | 0.23           | Smectite (Nontronite)             |
Physically, clay minerals can be distinguished from SEM results using backscattered SEM image CamScan CS-44 LB. Figure 1 (a) shows the presence of quartz mineral covered by nontronite.

![Figure 1](image)

**Figure 1.** Weekly compacted sandstone from the backscattered SEM (CamScan CS-44 LB). (a) quartz mineral that mostly covered by clay nontronite (b) Smectite Group (nontronite)

3. Results and Discussion

P-wave velocity (Vp) as a function of water saturation for all Ngrayong sample is shown in Figure 1. We could not achieve maximum water saturation from imbibition process, revealed that not all pores were filled by water. The measurements of Vp just before imbibition process (dry conditions) were relatively low ($880 \text{ m s}^{-1}$ to $1023 \text{ m s}^{-1}$), indicated the characteristic of weakly compacted sandstone.

![Figure 2](image)

**Figure 2.** Velocity measurement of rock samples from imbibition experiment. P-wave velocity changes due to the influence of water imbibition on the weekly compacted rocks of Ngrayong sandstone.

When compared to the overall results, the decrease of Vp and the first peak amplitude (Figure 3) occurred after the first stage of water imbibition was given to the rock sample. The increase of Vp when water saturation (Sw) decreasing until Sw < 0.7 is associated with the increase of sample density. At this stage, the results of water imbibition appeared in the pore, and gradually with the increase of imbibition, more pores were filled with water (70% pores) though there was still enough space in porous rock between the fluids. The remaining low frequency causes lack of pressure
differences. So, there is enough time for the fluid pressure to back to normal at one wave cycle. Vp increased gradually from Sw = 0.67 (sample B5); Sw = 0.74 (sample B2); Sw = 0.77 (sample B3), and 0.85 (sample B7). When water imbibition reached an average of Sw = 0.76 and provided uniform water distribution to almost all pores in the rock samples, the Vp increased. The volume of water in all pores contributes to reduce time for fluid pressure to return normally. P-wave frequency is quite high compared to the size of the patch so that the pressure between fluids in the pores does not reach equilibrium, resulting in the rock stiffness that lead to the increase of Vp. The increase of Vp is followed by the recovery of the first peak amplitude (Figure 3). Shifting peaks in Figure 3 indicate of signal attenuation from the seismic signal at an intermediate frequency. The first and second amplitude of P wave decreased as water saturation (Sw) increased at the range of 0.1 to 0.6 in B5 sample. The patches have irregular shape and randomly distributed. In addition, for the case of Ngrayong sample, the presence of smectite clay group can be one factor that lead to the trend of Vp lower than the limit of Gassmann Wood and Gassman Hill.

![Figure 3. Waveform (B5 sample) recorded from different Sw with a dashed line indicates shifting in the first peak of wave.](image)

4. Conclusion
The experimental results show that the saturation of weekly compacted rock can be detected and observed by the wave travel time and the amplitude of seismic signal. Nontronite, a member of smectite group, has been identified as a part of Ngrayong sandstone minerals. It seems that nontronite contribute to the decrease of Vp because water cause nontronite to swell. The swelling nontronite, then, push the mineral grain of quartz. When the contact between the grains of quartz mineral is weaker, the bulk modulus does not become larger.

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