# Laboratory measurements of velocity dispersion and wave attenuation in water saturated sandstones at low frequency

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**Summary**

We have conducted the laboratory measurements of elastic parameters of dry and partially water-saturated sandstones at frequency range from 2Hz to 500 Hz. Two sandstone samples with similar porosity of 20% but different permeability of 33 mD and 1830 mD. The measured results indicate that degree of water-saturation, rock permeability and measured frequency have significant impact on elastic properties and attenuation of the sandstones. With vacuum dry condition, both samples show ignorable velocity dispersion and low wave attenuation. With increasing water saturation, data suggests that even a minimum amount of gas (~1% gas saturation) can dominate bulk modulus of pore fluid, resulting in low bulk modulus and negligible dispersion of porous rock at low frequency. With fully water-saturated condition, dispersion of bulk modulus reveal three frequency bands: undrained, transition, and drained bands due to the presence of leaking boundary, in which pore fluid in rock frame communicates with fluid from pore pressure line. Bulk attenuation data show coupled response with bulk modulus dispersion. Shear modulus and shear attenuation data show that they are insensitive with the status of pore fluid saturation.

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**Introduction**

Seismic wave attenuation and velocity dispersion have drawn lots of attention in exploration seismology for decades, because those phenomenon are closely related to both the rock and fluid properties and may provide useful information on detecting the hydrocarbon through seismic techniques.

Fluid flow related dispersion and attenuation are commonly observed and discussed in the previous literatures. The Biot‘s (1956) inertial model describes miss match of movement between rock frame and pore fluids due to wave propagation. Later, people found that local heterogeneity can also generate pore pressure gradient and cause fluid flow, such as the squirt model ( O'Connell and Budiansky, 1977; Mavko and Nur, 1975), and double porosity model ( Pride and Berryman, 2003). However, the application of the dispersion and attenuation in exploration is still very limited. The reason of this lagged application probably comes from the gap between the model predictions and experimental results, especially for attenuation which are not widely available or reliable in laboratory measurement at seismic frequency range. Also, understanding of some observations in the laboratory measurement remains ambiguous.

Efforts must be made to exactly measure the velocity dispersion and wave attenuation in seismic frequency band. Spencer (1981) first successfully conducted the force-deformation method with strain amplitude around 10-6 and frequency below 100Hz in dry and water saturated rocks to measure the elastic and viscoelastic properties in seismic frequency. His results show strong dispersive modulus and frequent dependency of attenuation in water saturated samples. Liu et al. (1983) discussed the technique difficulties and challenges to carry out such experiments of applying such small amplitude to simulate in-situ seismic strain amplitude. The techniques were further developed by Batzle et al. (2006), who obtained and published several sets of seismic frequency velocity and attenuation data from various reservoir rocks. Meanwhile, a low frequency measurement system has been developed in rock physics lab at UH, utilizing the force deformation principle. This system can measure the velocity and attenuation in fluid filled porous rocks at seismic frequency range (2-500 Hz).

**Apparatus and Principles**

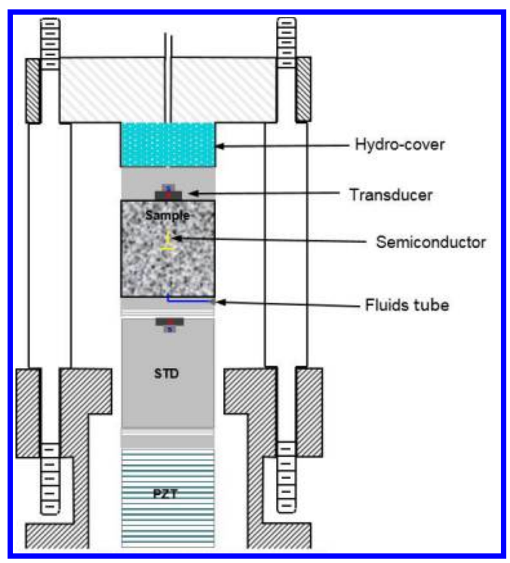



Figure 1: the schematic of low frequency apparatus

Figure 1 is the schematic of low frequency apparatus in rock physics lab at UH. The measured sample is placed in a pressure vessel, so that both confining pressure and pore pressure can be stressed to the sample. The confining pressure is supplied by a compressed nitrogen cylinder with a pressure regulator. Currently the maximum pressure can reach 6000 psi. The pore pressure is supplied and controlled by a digital pump, with various fluids as desired by experiment specific purposes.

Under predefined confining pressure, pore pressure and saturation conditions, the function generator sends out a continuous harmonic voltage wave with its frequency and amplitude. This voltage signal is supplied to a linear power amplifier to obtain a harmonic current wave, with desired current level. The current is used to drive a vibration to generate a harmonic mechanical vibration. The rock specimen and standard aluminum are deformed by the vibration. Both axial and radial strains are detected dynamically by the strain gages attached to the surfaces of samples and standard aluminum. The Wheatstone bridges output voltage waveforms to a special weak signal amplifier. The Young's modulus E and Poisson ratio ν of measured sample are obtained by comparing the strains detected in the sandstone and aluminum standard,

$$E_{sample} = E_{std}\frac{\varepsilon_{std\perp}}{\varepsilon_{sample||}} \qquad \nu = \frac{\varepsilon_{||}}{\varepsilon_{\perp}} \qquad (1)$$

The bulk K and shear G of samples can be calculated by relations

$$K = \frac{E}{3(1-2\nu)} \qquad G = \frac{E}{2+2\nu} \qquad (2)$$

The extensional attenuation equals to the tangential of the phase difference between strain and stress θ (White, 1983; Paffenholz and Burkhardt, 1989):

$$1/Q_E = \tan(\theta) \qquad (3)$$

The other attenuation parameters are related to each other through these three equations (Winkler and Nur, 1979):

$$\frac{(1-\nu)(1-2\nu)}{Q_P} = \frac{1+\nu}{Q_E} - \frac{2\nu(2-\nu)}{Q_S} \qquad (4)$$

$$\frac{1-2\nu}{Q_K} = \frac{3}{Q_E} - \frac{2(\nu+1)}{Q_S} \qquad (5)$$

$$\frac{1+\nu}{Q_K} = \frac{3(1-\nu)}{Q_P} - \frac{2(1-2\nu)}{Q_S} \qquad (6)$$

Where $Q_P$, $Q_S$ and $Q_K$ are the P-wave, S-wave and bulk quality factor respectively.

## Samples and experimental procedure

The physical characteristics of two sandstone samples (table 1) show that two samples with similar porosity of 20% but different permeability of 33 mD and 1830 mD. So we were expecting to see the different dispersion and attenuation result between these two samples. The low frequency measurements is firstly performed under vacuum dry condition at different confining pressures. Then the sample is saturated with distilled water at a constant differential pressure 3000 Psi. Also we use digital pump to manipulate flow rate of water to quantify the partial water saturation. All measurements are conducted at room temperature.

| Sample | Bentheimer | Bandera |
|---|---|---|
| Porosity (%) | 24.4 | 19.9 |
| Permeability (md) | 1830 | 33 |
| Grain density (g/cc) | 2.62 | 2.69 |
| Bulk density (g/cc) | 1.98 | 2.155 |

Table 1: physical characteristics of two samples

## Results

Under vacuum-dry condition, the measured bulk modulus and attenuation for Bentheimer and Bandera sandstone at different confining pressures (Figure 2) show that there is small dispersion and attenuation. Bulk modulus increase with confining pressure, and Bandera sandstone is more pressure-dependent than Bentheimer sandstone. The general trend of bulk attenuation is that it increase with frequency, and decrease with confining pressure. Bandera's bulk attenuation is more dispersive than Bentheimer.

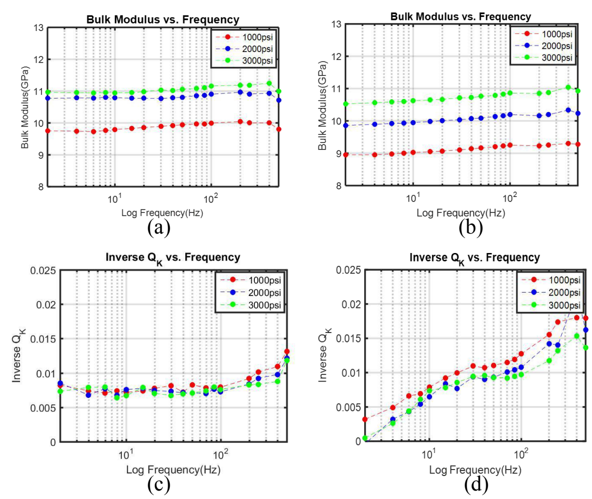



Figure 2: The measured (a) bulk modulus of Bentheimer sandstone, (b) bulk modulus of Bandera sandstone, (c) bulk attenuation of Bentheimer and (d) bulk attenuation of Bandera at different confining pressures (1000psi, 2000psi, 3000psi) under vacuum dry condition.

In order to observe the effect of partial gas/water-saturation on velocity dispersion and attenuation, the imbibition process is performed during low-frequency measurement.

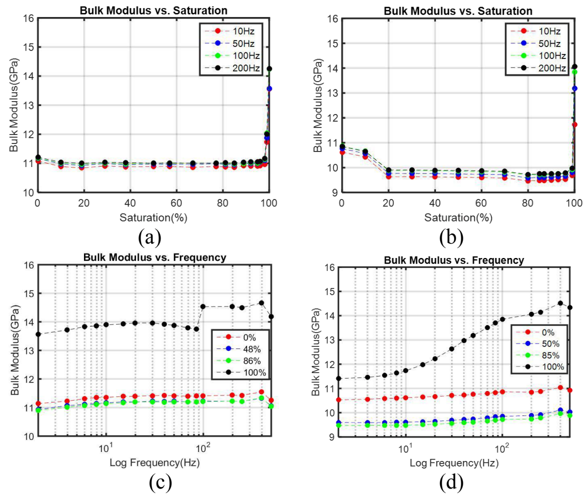



Figure 3: The measured (a) bulk modulus of Bentheimer sandstone and (b) bulk modulus of Bandera sandstone as a function of water saturation; The measured (c) bulk modulus of Bentheimer sandstone, (d) bulk modulus of Bandera sandstone as a function of frequency for different degree of water saturation. Differential pressure is constant (3000 psi) in the process of injecting water.

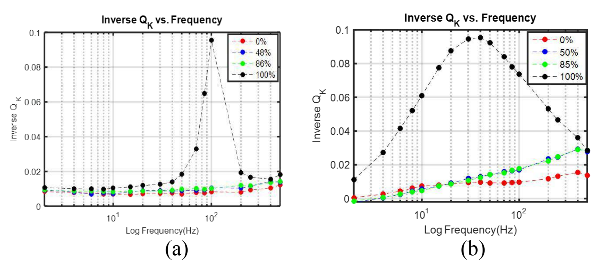



Figure 4: The measured (a) bulk attenuation of Bentheimer and (b) bulk attenuation of Bandera as a function of frequency for different degree of water saturation. Differential pressure is constant (3000 psi) in the process of injecting water.

The sample is saturated with distilled water at a constant differential pressure of 3000 psi. As seen in figure 3 (a, b, c, d) and figure 4(a, b), measured data reveals four fluid effects on bulk modulus and bulk attenuation:

I. There's a decrease of bulk modulus at initial water saturation (figure 3 a, b). This is mainly due to the moisture effect, which may has chemical reaction with rock, resulting in modulus decrease. For Bandera sandstone, as the point at 20 % water saturation was measured after saturating for one night, moisture has enough time to distribute in the whole sample, so the chemical reaction reaches maximum which causes modulus drop a lot.

II. With increasing water saturation ( >20%), bulk modulus of sandstone tends to remain a constant until approaching fully saturated condition (~1% gas saturation), then it increases sharply (figure 3 a, b). Data suggests that even a minimum amount of gas can dominate bulk modulus of pore fluid, which indicates water-gas at the iso-stress condition, resulting in low bulk modulus and negligible dispersion of porous rock at frequency ranged from 2Hz to 500Hz (figure 3 c, d).

III. With fully water-saturated condition, dispersion of bulk modulus reveals three frequency bands (figure 3 c, d - black line): undrained, transition, and drained bands due to the presence of leaking boundary, in which pore fluid in rock frame communicates with fluid from pore pressure line. Tranision of bulk modulus form low to high seems controlled by permeability, The lower permeability (Bandera sandstone) will cause wide transition band.

IV. Bulk attenuation data (figure 4 a, b) show coupled response with bulk modulus dispersion. It slightly increase with water saturation and frequency until approaching fully water saturated condition. With fully saturaiton, The dramatically increased attenuation associates time scales of fluid resonance between rock frame and pore-inlet tube.

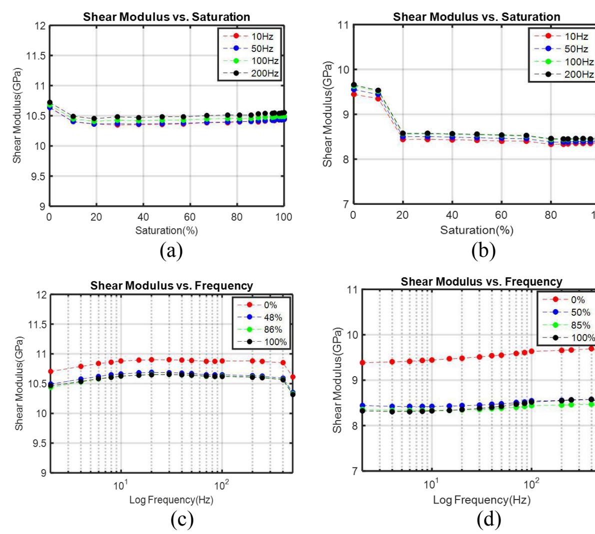
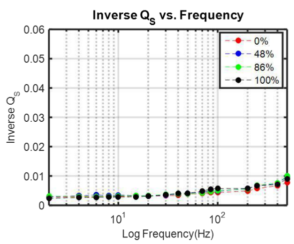
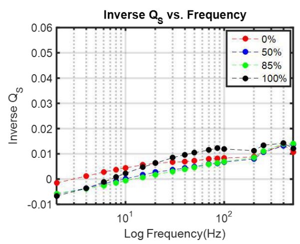



Figure 5: The measured (a) shear modulus of Bentheimer sandstone and (b) shear modulus of Bandera sandstone as a function of water saturation; The measured (c) shear modulus of Bentheimer sandstone, (d) shear modulus of Bandera sandstone as a function of frequency for different degree of water saturation. Differential pressure is constant (3000 psi) in the process of injecting water.

In contrast with the behavior of the dispersion and attenuation of buk modulus, fluid effect on shear modulus (figure 5 a, b, c, d) and shear attenuation (figure 6 a, b) show different reponse. Due to the moisture effect, there's a decrease of shear modulus at initial water saturation, especially for Bandera sandstone, which was measured after one night at 20% water saturation. With increasing water saturation, shear modulus tends to remain a constant, and it show negligible dispersion in frequency domain (figure 5 c, d). Shear attenuation data (figure 6 a, b) shows that there are small shear attenuation for porous rock at frequency ranged from 2Hz to 500Hz, and they are insensitive with the status of pore fluid saturation.



(a)



(b)

Figure 6: The measured (a) shear attenuation of Bentheimer and (b) shear attenuation of Bandera as a function of frequency for different degree of water saturation. Differential pressure is constant (3000 psi) in the process of injecting water.

## Conclusions

In this low frequency measurement, we have studied the elastic parameters of dry and partially water-saturated sandstones. Two sandstone samples with similar porosity of 20% but different permeability of 33 and 1830 mD. The measured results indicate that degree of water-saturation, rock permeability and measured frequency have significant impact on elastic properties and attenuation of the sandstones. Under vacuum-dry condition, both samples show ignorable velocity dispersion and low wave attenuation. With increasing water saturation, bulk modulus of sandstone tends to remain a constant until near fully saturated condition (~1% gas saturation), then increase sharply. Data suggests that even a minimum amount of gas can cause low bulk modulus and negligible dispersion. With transition from partial gas saturation to fully water saturated status, there is a trend to dramatically increase bulk modulus with dispersion from a low to a high value, and transition band ranges from 2 Hz to 500 Hz. In addition, wave attenuation data show consistent response in frequency domain. The dramatically increased attenuation associates time scales of fluid resonant between rock frame and pore-inlet tube. Shear modulus and shear attenuation data show that they have no relations with status of pore fluid saturation.

**EDITED REFERENCES**

Note: This reference list is a copyedited version of the reference list submitted by the author. Reference lists for the 2017 SEG Technical Program Expanded Abstracts have been copyedited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

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