

Low-frequency measurements of the mechanical parameters of sandstone with low permeability

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SUMMARY

A study of the pore fluid effects on the elastic and anelastic properties of sedimentary rocks is important for interpreting seismic data obtained for reservoirs as well as for monitoring the fluid movement during both fluid extraction in producing fields and injection of CO₂ for storage purposes. In most sedimentary rocks low intrinsic permeability and, as a consequence, low fluid mobility lead to a situation when relative motion between pore fluid and rock skeleton has significant influence on acoustic wave propagation even at seismic frequencies. Therefore, in many cases the experiments conducted only at seismic frequencies are not sufficient to validate commonly used theoretic models of elastic moduli dispersion and attenuation.

We present data obtained with a new version of low-frequency laboratory apparatus designed for measurements of Young's moduli and extensional attenuation of rocks at seismic (1-400 Hz) and teleseismic (≤ 1 Hz) wave frequencies. The apparatus can operate at confining pressures from 0 to 70 MPa. Elastic and anelastic parameters of dry and water-saturated sandstone quarried in Donnybrook, Western Australia, were measured at various confining pressures and room temperature ($\sim 20^{\circ}$ C). A peak of attenuation in a water-saturated sample with 14.8% porosity and 7.8 mD permeability was found at frequency 0.8 Hz.

INTRODUCTION

It was indicated by Batzle *et al.* (2006) for sedimentary rocks with low intrinsic permeability and low fluid mobility the pore pressure may be out of equilibrium even at seismic frequencies (the high frequency regime). Therefore, to validate the applicability of theoretic models of fluid substitution and theories of elastic moduli dispersion and attenuation to analysis of the low-permeability rocks, the measurements should be conducted in the frequency range significantly exceeding the range of seismic frequencies.

The first measurements of water saturated sandstone were performed by Spencer (1981) who observed significant Young's moduli dispersion and attenuation at frequencies of a few hundreds of Hertz in Navajo sandstone. Later it was shown that Spencer's results can be explained by the open-pore boundary conditions of the sample (White, 1986; Dunn,

1986) and, to some extent, by anelasticity of the elastic constants of rocks (Dunn, 1986). Using the Cole-Cole approach Batzle *et al.* (2006) demonstrated that a peak of attenuation for water saturated sandstone with low permeability should be at frequency < 1 Hz. This result predicts that Gassmann theory is not applicable to low permeable sandstones saturated with distilled water even at seismic frequencies.

We experimentally tested the calculations conducted by Batzle *et al.* (2006) using a new low-frequency apparatus based on stress-strain relationship. The apparatus measures Young's moduli and extensional attenuation of rocks at seismic (1-400 Hz) and teleseismic (0 – 1Hz) frequencies and at strain amplitudes $10^{-8} - 10^{-6}$.

APPARATUS

The mechanical assembly of the apparatus is presented in Figure 1. The assembly comprises two massive steel platforms and a set of units between them, which includes a hydraulic actuator, a Hoek triaxial cell, a piezoelectric stack actuator PST 1000/35/60 (APC International Ltd) with the limit of maximum load of 70,000 N and with the frequency of its mechanical resonance > 20 kHz, one aluminium calibration standard, and two aluminium plugs having passages for a fluid injection. The main purpose of using the platforms is to reduce the spurious mechanical resonances in the assembly.

A rock sample to be tested with two strain gauges glued to its surface (see Figure 2) is placed inside a sleeve, which is mounted within the triaxial cell. The fluid passages in the aluminium plugs attached to the sample enable the flow of fluids through the sample and provide the means for pore pressure control. The cell and the hydraulic actuator are connected via fluid lines with two hydraulic pumps providing radial and axial static forces applied to the specimen.

The schematic diagram of the electrical part of the apparatus is shown in Figure 3. The periodic voltage generated by an oscillator is applied via a power amplifier to the multilayer piezoelectric adaptor, where it transforms into mechanical stress. The stress causes displacements in the aluminium standard and specimen mounted in series, which, in turn, modulate the conductivity of the strain gauges coupled with the standard and rock sample. A set of electrical bridges transforms the modulated conductivity into electrical signals, which, after digitizing by an analogue-digital converter, are received by an acquisition computer, where the signals are

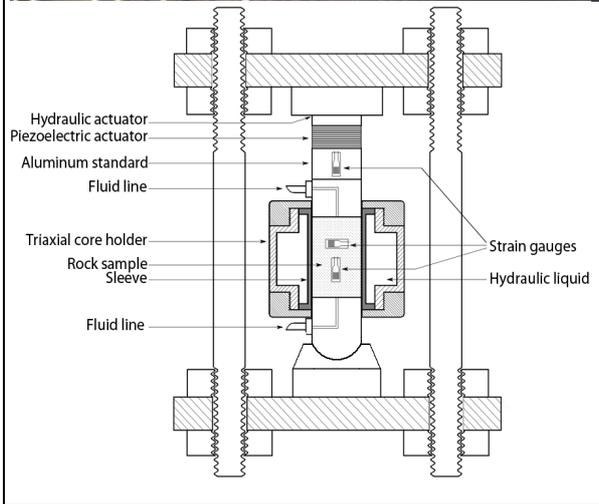
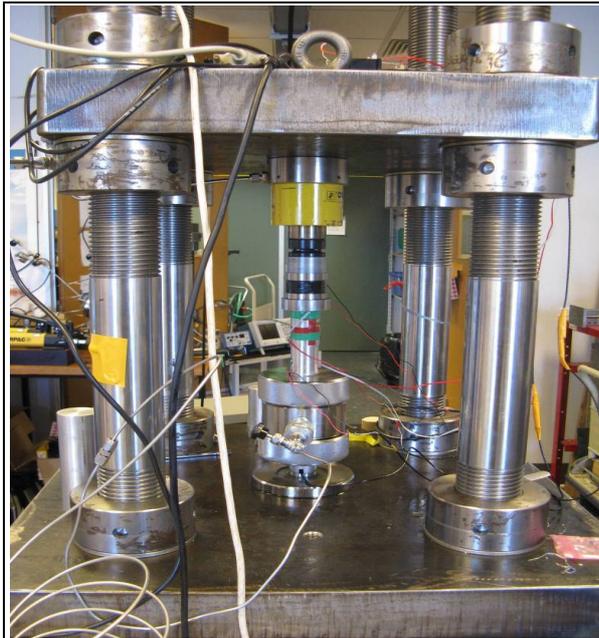


Figure 1. The mechanical assembly of the low-frequency laboratory apparatus.



Figure 2. The sample of Donnybrook sandstone with radial and axial strain gauges glued to its surface.

averaged and processed. The value of extensional attenuation is derived from the phase shift between the stress applied to a sample strain and the strain in the sample caused by that stress.

METHOD AND OPERATION

For our low-frequency measurements we modified a version of the stress-strain technique employed by Spencer (1981), Paffenholz and Burkhardt (1989), and Batzle *et al.* (2006). Here we describe our approach in more detail.

The signals corresponding to the axial and radial components of the strain in the rock sample are detected by the strain gauges, one of which is aligned with axial direction and the second is orthogonal to the first one. These signals are used to calculate the Young's modulus and Poisson's ratio.

We assume that periodical stress is applied along z-axis, then from Hooke's law (e.g. Mavko *et al.*, 2009)

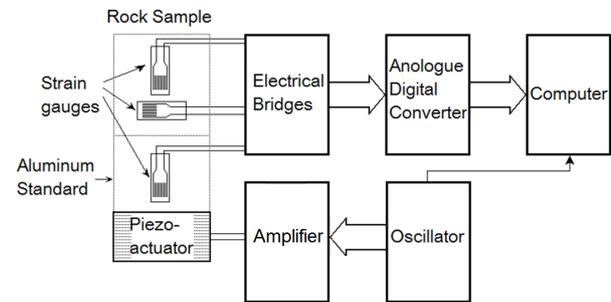


Figure 3. The electrical schematics of the low-frequency laboratory apparatus.

$$\varepsilon_{ij} = \frac{1}{E}(1 + \nu)\sigma_{ij} - \nu\delta_{ij}\sigma_{aa}, \quad (1)$$

where ε_{ij} are the elements of the sample strain tensor; σ_{ij} are the elements of the stress tensor; $\sigma_{aa} = \sum_{i=1}^3 \sigma_{ii}$; we can find the Poisson's ratio ν

$$\nu = \frac{c - \frac{\varepsilon_{xx}}{\varepsilon_{zz}}}{1 + c - 2c \cdot \frac{\varepsilon_{xx}}{\varepsilon_{zz}}}, \text{ where } c = \frac{\sigma_{xx}}{\sigma_{zz}}. \quad (2)$$

The Young's modulus of the rock E can be found from Eq. (1):

$$E = \sigma_{zz} \frac{(1 + \nu)(1 - 2\nu)}{2\nu\varepsilon_{xx} + (1 - \nu)\varepsilon_{zz}}, \quad (3)$$

The stress σ_{zz} can be expressed through the parameters of the aluminium standard as $E_{al}\varepsilon_{zz}^{al}$, where E_{al} is the known Young's modulus and ε_{zz}^{al} is a measured amplitude of axial strain. So, the Young's modulus of the rock is

$$E = E_{al} \frac{\varepsilon_{zz}^{al}(1+\nu)(1-2\nu)}{2\nu\varepsilon_{xx} + (1-\nu)\varepsilon_{zz}} \quad (4)$$

It can be shown that the coefficient c , which is required for the determination of the Poisson's ratio ν in Eq. (2), is equal to

$$c = k_l \frac{rL_s}{(R^2 - r^2)L \cdot E_{al}} \frac{\varepsilon_{xx}}{\varepsilon_{zz}^{al}}, \quad (5)$$

where k_l is the bulk modulus of the hydraulic oil; L_s and r are the length and radius of the specimen; R is the internal radius of the core holder. The dependence of the bulk modulus of the hydraulic oil k_l on pressure was measured at ultrasonic frequency 1 MHz and presented in Figure 4.

Using the Young's modulus determined by Eq. (4), we can find compressional and shear velocities:

$$V_p = \sqrt{\frac{E(1-\nu)}{(1+\nu)(1-2\nu)\rho}}, \quad V_s = \sqrt{\frac{E}{2(1+\nu)\rho}}, \quad (6)$$

where ρ is the density of the rock.

The extensional attenuation Q_E^{-1} in the sample can be estimated as follows. The periodic signals, which are detected by axial strain gages coupled with the aluminium standard and the rock sample, are averaged and subjected to Fourier transform. The resulting complex Fourier transform amplitudes A_{al} and A_s , which are calculated at the frequency of the periodic voltage generated by the oscillator, are used to

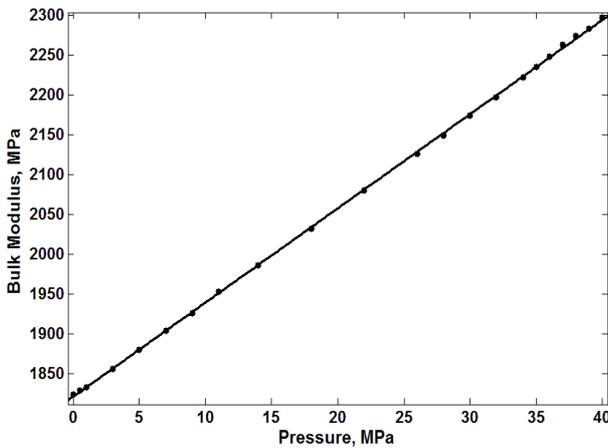


Figure 4. The dependence of the bulk modulus of hydraulic oil k_l on confining pressure.

estimate the attenuation Q_E^{-1} :

$$Q_E^{-1} \approx \frac{\text{Im}(A)}{\text{Re}(A)}, \quad (7)$$

where $A = \frac{A_s}{A_{al}} \cdot \frac{|A_{al}|}{|A_s|}$, $|A_{al}|$ and $|A_s|$ are the absolute values of the amplitudes A_{al} and A_s , which correspond to the signals obtained from the axial strain gauges coupled with the aluminium standard and rock sample respectively.

The example of the signals obtained from this sample at the frequency of the periodical stress oscillations 10 Hz and at confining pressure 15 MPa, is given in Figure 5.

The results obtained for the sandstone sample at three frequencies of 1, 10 and 100 Hz, are presented in Figures 6-8. The experiments were carried out at room temperature and at confining pressures from 3 to 40 MPa. The physical parameters of the water saturated sample are as follows: the density is 2245 kg/m³, porosity and permeability are 14.8% and 7.8 mD correspondingly. The diameter of the sample is 38mm, the length is 70 mm.

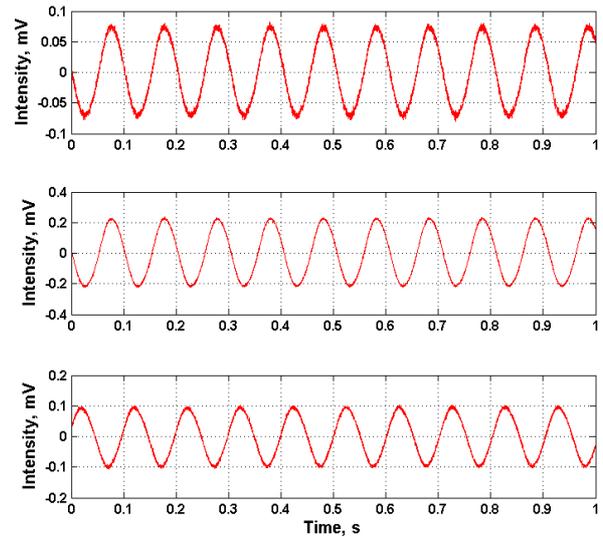


Figure 5. Signals obtained from the water saturated sandstone at the frequency of the periodical stress oscillations 10 Hz and at confining pressure 15 MPa. The top signal was obtained from the gauge attached to the aluminium standard, the middle and bottom signals were obtained correspondingly from the axial and radial gauges attached to the rock sample. The number of averages is 100.

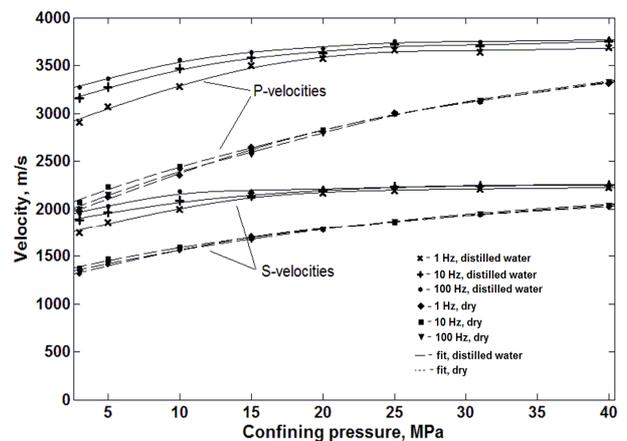


Figure 6. P- and S-wave velocities obtained for the water saturated and dry sandstone at three frequencies: 1, 10 and 100 Hz.

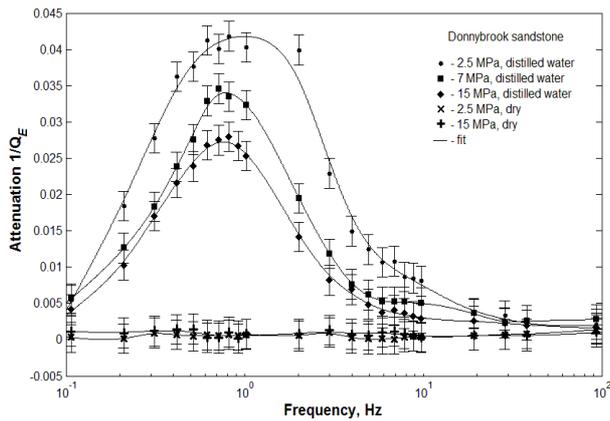


Figure 7. The extensional attenuation Q_E^{-1} measured for the water saturated sandstone at three confining pressures of 2.5, 7 and 15 MPa. Pore pressure is 0.1 MPa.

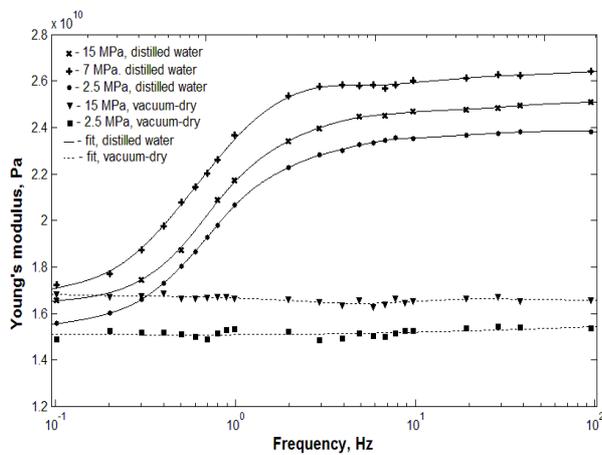


Figure 8. Dependencies on frequency for Young's moduli of dry and water saturated sandstone. Pore pressure and confining pressures for the water saturated and dry samples are the same as in Fig. 7.

The results obtained for V_p and V_s in water saturated and dry sandstone at three low frequencies are presented in Figure 6.

The extensional attenuation and Young's modulus presented in Figures 7 and 8 were measured at three confining pressures: 2.5, 7 and 15 MPa. In all our measurements the number of signal averages was 100.

CONCLUSIONS

We presented a new version of the low frequency laboratory apparatus operating at seismic frequencies and at either confining or uniaxial pressures from 0 to 70 MPa. The apparatus utilizes a stress-strain technique and measures the complex Young's modulus, extensional attenuation and Poisson's ratio of the rock sample at the range of strain amplitudes between 10^{-8} and 10^{-6} . The apparatus can also be incorporated with an ultrasonic system to combine low- and high-frequency measurements.

The results of our measurements of Donnybrook sandstone demonstrate that the peak of the extensional attenuation in the water saturated sample takes place at frequency 0.8 Hz. This frequency is considerably lower than the dominant frequencies of the seismic waves used for recording in exploration seismology (10-100 Hz). Our results confirm the statements of Batzle *et al.* (2006) that for low-permeability rocks seismic frequencies do not necessarily correspond to the low frequency limit of seismic dispersion.

Our measurements also show that Young's moduli increase considerably in the water saturated sample in comparison with the dry one. The dispersion of the Young's moduli of dry sandstone was within the accuracy of our measurements.

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