Laboratory apparatuses for measuring seismic attenuation in fluid-saturated rocks

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Abstract

Intrinsic wave attenuation at seismic frequencies is strongly dependent on rock permeability and on fluid properties and saturation. However, in order to extract this information from seismic, experimental studies on attenuation are needed for a better understanding of such dependency. Here, we briefly describe two apparatuses developed to measure seismic attenuation in fluid-saturated rocks: the SWAM and the BBAV. Additionally, we described some advantages and drawbacks of these two machines through comparisons with six other experimental setups that have been built in the last 25 years for similar studies. All these apparatuses measure frequency-dependent attenuation in dry and partially fluid-saturated rock samples under small strains which are comparable to strains caused by seismic waves in the Earth.

Introduction

From a geophysical perspective, understanding seismic wave attenuation in rocks is of great importance because most of the information available on the structure and composition of the subsurface is obtained from seismic data. In particular, since the presence of pore fluids cause significant increase of attenuation in rocks, information about their properties and saturation could potentially be obtained from seismic data.

Attenuation is strongly related to the capacity of fluids to move (therefore, to permeability) as a consequence of transient stress perturbation, i.e., the propagating wave. Therefore, the resulting attenuation is typically frequency dependency.

Experimental studies on low frequency attenuation of rocks have been reported in the last 30 years (e.g. Murphy 1982). They indicated the importance of the pore-saturating fluids in inducing a frequency-dependent seismic response of the rock. Such behavior contrasts with the case of a dry rock for which a negligible dependency of the seismic response on frequency was observed (e.g., Tisato and Madonna, 2012).

Batzle et al. (2006) explained the frequency-dependency of attenuation in fluid-saturate rocks in terms of fluid mobility defined as the ratio of rock permeability on fluid viscosity and pore pressure distribution within porous rocks. Experimental evidence to support this has been provided, for example, for sandstones (Batzle et al. 2006) and carbonates (Adam et al. 2006).

The SWAM

The Seismic Wave Attenuation Module (SWAM, Figure 1, Madonna and Tisato, 2013) has been developed to experimentally measure attenuation in extensional mode and the Young's modulus fluid-saturated rock samples, 60 mm in length and 25.4 mm in diameter, in a gas medium high-pressure rig (Paterson rig, Figure 2). The sample is sealed with a copper jacket. Attenuation at low seismic frequencies (0.01 to 100 Hz) is obtained.

The SWAM is suitable for natural rock samples and so far it has being tested using confining pressures up to 50 MPa and at room temperature.

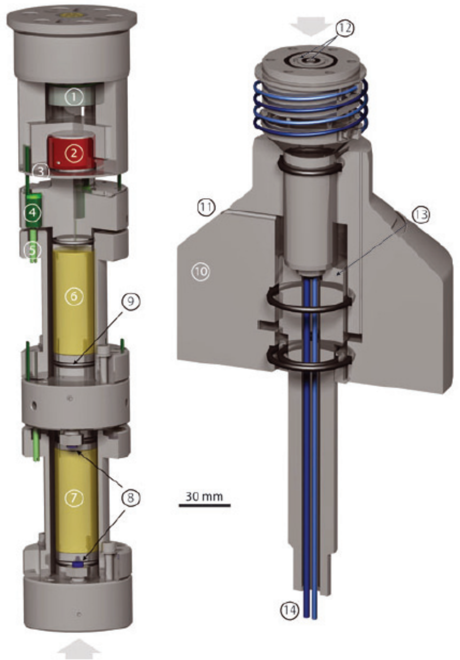

Figure 1. Sketch of the SWAM. After Madonna and Tisato (2013).

To calculate attenuation, both the applied force and the shortening of the sample are measured, employing Linear Variable Differential Transformers (LVDTs). The LVDTs allows for measuring the bulk shortening of the sample and, therefore, these measurements are suitable also to samples exhibiting high degree of heterogeneity.

This apparatus is designed to operate at a strain below 10^{-7}, in which rocks behave linearly. The accuracy of attenuation data is very high for the tested rock samples.

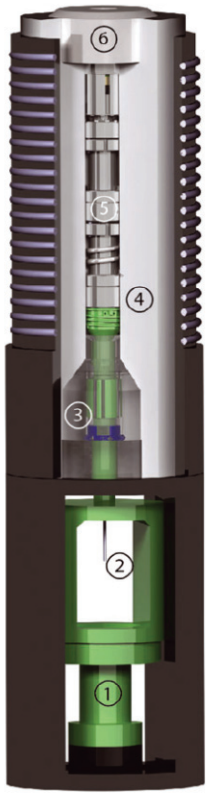

Figure 2. Sketch of the high-pressure triaxial testing apparatus (Paterson rig). After Madonna and Tisato (2013).

The BBAV

A pressure vessel called Broad Band Attenuation Vessel (BBAV, Figure 1, Tisato and Madonna, 2012) has being build, and successfully tested, to measure seismic attenuation employing the sub-resonance method, in the frequency range from 0.01 to 100 Hz. For these measurements, it generates a bulk strain around 10^{-6} in a 76 mm diameter and 250 mm long cylindrical sample.

The calibration results obtained with aluminum and Plexiglas are in good agreement with literature values. Berea sandstone samples were also tested. Dry samples exhibited always attenuation of ~0.01, while partially saturated samples exhibit attenuation between about 0.01 and about 0.1.

The BBAV is suitable to perform measurements under confining pressures up to 25 MPa.

More recently, an array of fluid pressure sensors has also being implemented on the BBAV (Figure 3, Tisato and Quintal, 2013). With this modification, a novel laboratory technique was proposed based on combining measurements of seismic attenuation with measurements of transient fluid pressure to investigate wave-induced fluid flow on the mesoscopic scale as a mechanism for seismic attenuation in partially saturated rocks.

Wave-induced fluid flow on the mesoscopic scale is a physical mechanism that may yield significant attenuation at seismic frequencies in fluid-saturated porous media (Pride et al., 2004). Mesoscopic scale is the scale much smaller than the wavelength and much greater than the pore sizes. Wave-induced fluid flow can be due to heterogeneities in fluid saturation (so called patchy saturation, White, 1975), or in the solid frame (Berryman and Wang, 2001) such as in fractured media. The passing seismic wave induces fluid pressure differences between regions of different compliances. The resulting pressure gradients induce diffusive fluid flow and, therefore, part of the energy involved in the wave propagation is lost due to viscous dissipation.

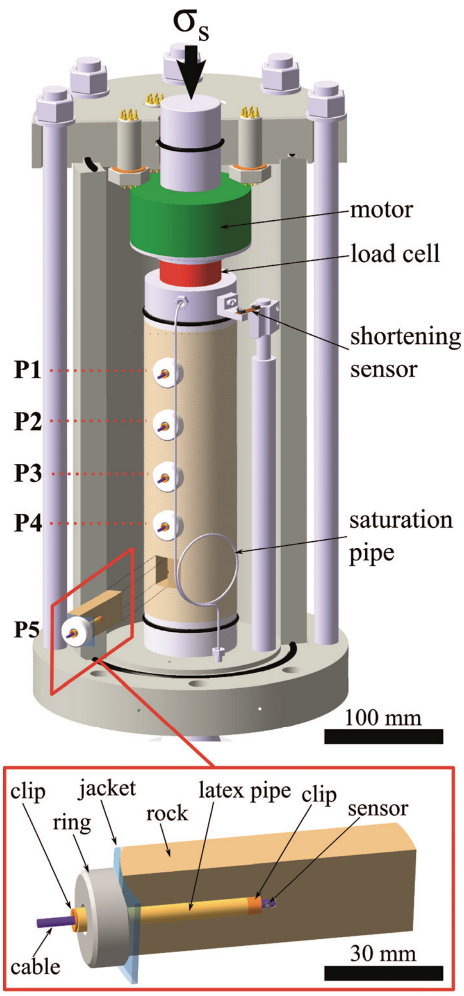

Figure 3. Sketch of the BBAV with fluid pressure sensors. Modified after Tisato and Madonna (2012) and Tisato and Quintal (2013).

Other experimental setups

Experimental studies on low frequency attenuation of rocks have been reported for several decades (e.g., Spencer, 1981, Peselnick and Liu, 1987; Paffenholz and Burkhardt, 1989; Batzle et al., 2006; Mikhaltsevitch et al., 2011; Takei et al., 2011; Figure 4).

Conceptually, the developed setups (Figure 4) machines are similar. They all include: (i) an actuator, to generate a force; (ii) a force sensor, to obtain the applied force; and (iii) displacement sensors, to obtain the strain. However, they differ on technical aspects; for example, different sensors are used.

Most of the machines, including the SWAM and the BBAV, use a piezoelectric actuator (PZA) to generate the required force. The motor consists of stacked piezoelectric elements. They work well under confining pressure. The advantage of using a PZA is that the actuator is sensitive to a small variation of voltage, which leads to high resolution in the measured displacement. No threshold voltage is required. They have a fast response in the time domain. They do not generate a magnetic field, which could interfere with the sensors nearby. Alternatively, a hydraulic shaker is applied (e.g., Spencer, 1981; Batzle et al., 2006).

Several force transducers are used to measure force. Most of the load cells use strain gauges (foil or semiconductor) as the sensing element attached to elastic elements. In the SWAM, LVDTs are instead employed as sensing element to record the change in length of the elastic material. The choice of employing the LVDTs was necessary to keep the same electronic conditioning for all the sensing elements, to avoid electronic artifacts. The attenuation measurement is based on the phase shift between the displacement of the elastic element and the tested material.

Conclusions

We described two apparatuses to measure seismic attenuation in fluid-saturated rocks recently developed at ETH Zurich. Additionally, we described some advantages and drawbacks of these two machines through comparisons with six other experimental setups that have been built in the last 25 years.

Acknowledgments

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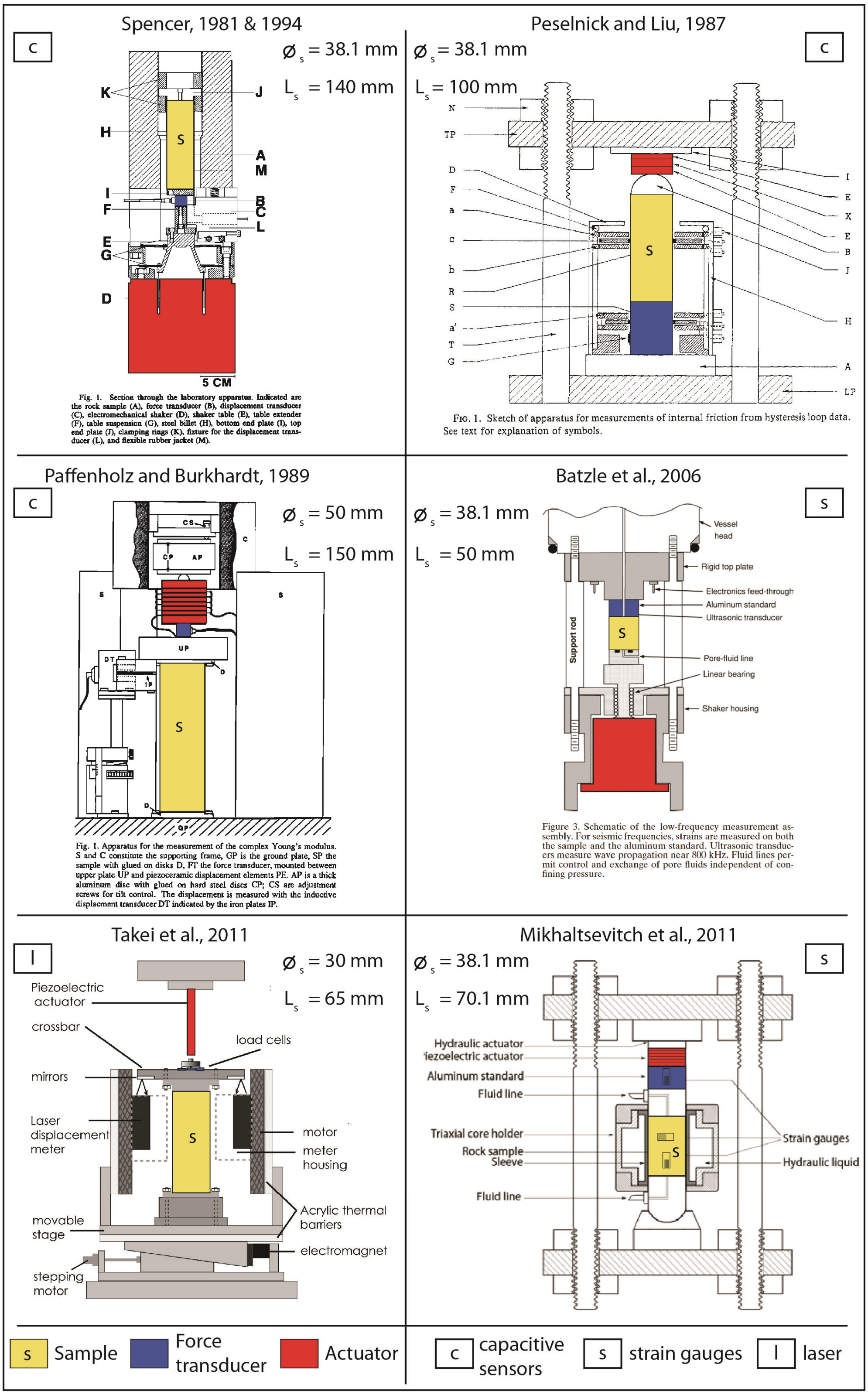
Spencer, 1981 & 1994

Fig. 1. Section through the laboratory apparatus. Indicated are the rock sample (A), force transducer (B), displacement transducer (C), electromechanical shaker (D), shaker table (E), table extender (F), table suspension (G), steel billet (H), bottom end plate (I), top end plate (J), clamping rings (K), fixture for the displacement transducer (L), and flexible rubber jacket (M).

Peselnick and Liu, 1987

FIG. 1. Sketch of apparatus for measurements of internal friction from hysteresis loop data. See text for explanation of symbols.

Paffenholz and Burkhardt, 1989

Fig. 1. Apparatus for the measurement of the complex Young's modulus. S and C constitute the supporting frame, GP is the ground plate, SP the sample with glued on disks D, FT the force transducer, mounted between upper plate UP and piezoceramic displacement elements PE. AP is a thick aluminum disc with glued on hard steel discs CP; CS are adjustment screws for tilt control. The displacement is measured with the inductive displacment transducer DT indicated by the iron plates IP.

Batzle et al., 2006

Figure 3. Schematic of the low-frequency measurement assembly. For seismic frequencies, strains are measured on both the sample and the aluminum standard. Ultrasonic transducers measure wave propagation near 800 kHz. Fluid lines permit control and exchange of pore fluids independent of confining pressure.

Takei et al., 2011

Mikhaltsevitch et al., 2011

Figure 4. Other setups to measure attenuation in extensional mode. The main common parts of the machines are highlighted in color: actuator, force transducer, and sample. The setups differ from each other mainly due to the different displacement sensors used (after Madonna, 2012).