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# Shale dynamic properties and anisotropy under triaxial loading: Experimental and theoretical investigations

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## Abstract

This paper is concerned with the experimental identification of the whole dynamic elastic stiffness tensor of a transversely isotropic clayrock from a single cylindrical sample under loading. Measurement of elastic wave velocities (pulse at 1 MHz), obtained under macroscopically undrained triaxial loading conditions are provided. Further macroscopic (laboratory scale) interpretation of the velocity measurements is performed in terms of (i) dynamic elastic parameters; and (ii) elastic anisotropy. Experiments were performed on a Callovo-Oxfordian shale, Jurassic in age, recovered from a depth of 613 m in the eastern part of Paris basin in France. Moreover, a physically-based micromechanical model is developed in order to quantify the damaged state of the shale under loading through macroscopic measurements. This model allows for the identification of the pertinent parameters for a general transversely isotropic orientational distribution of microcracks, superimposed on the intrinsic transverse isotropy of the rock. It is directly inspired from experimental observations and measurements. At this stage, second- and fourth-rank tensors $\alpha_{ij}$ and $\beta_{ijkl}$ are identified as proper damage parameters. However, they still need to be explicited in terms of micromechanical parameters for the complex case of anisotropy. An illustration of the protocole of this microstructural data recovery is provided in the simpler case of isotropy. This microstructural insight includes cavities geometry, orientation and fluid-content.

*Keywords:* Shale; Elastic wave velocity; Anisotropy; Damage; Effective medium

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## 1. Introduction

### 1.1. Callovo-Oxfordian shale

Clayrocks, and shales in particular, represent approximately two-third of all sedimentary rocks in shallow earth crustal rocks. In oil and gas drilling operations, shales constitute 80% of all the drilled sections, mainly because they overlie most hydrocarbon bearing reservoirs (immature shales). Furthermore, several countries are considering clayrocks as possible host lithologies for radioactive waste repository, and therefore carrying out research programs to estimate feasibility of such solution. In this trend, the french agency for radioactive waste management, ANDRA, is evaluating the reliability of the Callovo-Oxfordian layer, Jurassic in age, located in the eastern part of France (around Bure), at a depth ranging from 400 m to 700 m. The static mechanical and transport properties of this clayrock have been largely studied for the past few years (complete bibliography in Escoffier (2001)). However, very few elastic wave velocity measurements, all at atmospheric pressure, were performed, and no velocity data at all under mechanical loading are available in the literature for this rock. Indeed, elastic wave velocity measurements are well known as being very sensitive to damage in rocks (Schubnel and Guéguen, 2003), in particular to evaluate damage in the EDZ (excavation damaged zone). The main outcome of interest here from these research programs is the transversely isotropic nature of Bure clayrock

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demonstrated experimentally in several labs for several locations and depths in the layer (David et al., 2005). The main plane of symmetry is quasi-horizontal and corresponds to a very fine layering (bedding).

### 1.2. Shale lithologies

In general, the monitoring of elastic velocities in shales under mechanical loading are relatively uncommon in view of the abundance of this lithology among shallow earth crustal rocks (Stanley and Christensen, 2001). This relative rareness is partly due to: (i) the inherent difficulty of transmitting transducer signals through the waterproof pressure chamber in a loading apparatus; and, on the other hand, (ii) the specificities in preparing and handling shale samples for mechanical testing (chemical sensitivity to water, extremely low permeability...). Most of the dynamic experimental studies reported in the literature on shale samples were performed under hydrostatic loading conditions (Johnston and Toksöz, 1980; Jones and Wang, 1981; Lo et al., 1986; Johnston and Christensen, 1995; Hornby, 1998; Stanley and Christensen, 2001). However, elastic wave velocity measurements on shales are reported by Yin (1992) under triaxial (and polyaxial) loading, and by Podio et al. (1968) under uniaxial loading.

### 1.3. Main goals

The specific experimental setup available in our laboratory allows for the simultaneous measurement of five different velocities and two directions of strain on the same rock sample, under triaxial and pore pressure-controlled conditions of loading. This procedure reduces the number of experiments on differently oriented samples usually needed to identify the dynamic properties of a transversely isotropic rock. It also minimizes the errors due to the particular difference between two samples of the supposedly same lithology or same physical state (stress, hydration and saturation histories since recovery).

The main outcomes of this experiment are: (i) identification of the apparent dynamic stiffness tensor of the Callovo-Oxfordian shale from elastic wave velocity measurements; (ii) assessment of velocity anisotropy, and its evolution under triaxial loading (Thomsen, 1986). This last step allows for the quantification of the intrinsic and stress-induced anisotropies, leading eventually to an estimation of the microcracks density and distribution evolutions in the shale sample under loading (Sayers and Kachanov, 1995; Sayers, 1999).

## 2. Experimental procedure

### 2.1. Experimental setup

The rock physics group of the Ecole Normale Supérieure recently acquired a triaxial cell designed for the exploration of the hydromechanical behavior of shallow earth crustal rocks. This apparatus allows for pore pressure, hydrostatic and deviatoric stresses to be applied independently on a cylindrical porous rock sample (up to $\varnothing 40$ mm × $L80$ mm). The pore, confining and axial pressures may reach 100, 300 and 800 MPa (on the largest samples), respectively. The originality of this loading cell is to allow for a maximum of 32 waterproof signal wires through the wall of the pressure chamber. The control and data acquisition are performed by means of a dedicated software designed in Labview™ environment. The lab is temperature-controlled with an accuracy of ±0.5 °C.

### 2.2. Sample description and preparation

The tested shale was provided by the french agency for radioactive waste management, ANDRA. The received large cores ($\varnothing 90$ mm × $L280$ mm) were recovered in 1995 from a depth of 613 m in the eastern part of Paris basin, near Bure, in France (MSE 101 borehole). These cores were since preserved in a so-called T1 cell, isolated from gas exchange with the storing environment, and maintained under small, almost hydrostatic, confining stress ($\lesssim 1$ MPa). The sample is dry-cored perpendicularly to the horizontal bedding, ground for parallel end faces, and preserved in waterproof membranes. It is 60 mm long with a 30 mm diameter. For the few days before testing, during the phase of transducers gluing and curing, the sample is maintained in a 100% relative humidity (RH) environment in order to avoid drying and to ensure reproducible initial conditions for different samples with different hydric histories (as much as it is possible with clayrocks). Usually, after putting it in 100% RH atmosphere, the mass of the sample increases then levels off. However, it is assumed that the sample may still be superficially unsaturated. It is tested under macroscopically undrained conditions within the loading cell.

### 2.3. Transducers arrangement

For the experiment reported here, 22 signal wires were used. Both axial and circumferential strain gages and nine piezoelectric transducers were glued on the cylindrical sample. However, the strain gages signals are rapidly lost at the beginning of this test. The specific arrangement of piezoelectric transducers allows for the measurement of five different elastic velocities as shown in Fig. 1. Indeed, let us define the reference frame $(x_1, x_2, x_3)$, with $(x_1, x_2)$ being the horizontal bedding plane of symmetry of the transversely isotropic cylindrical shale sample. Then, measurements of three compressional velocities and two shear velocities, in three different directions are provided. These velocities are referenced with respect to the bedding plane, *i.e.*, $V_P(0°)$ for the bedding-parallel compressional velocity, $V_P(45°)$ for the 45°-to-bedding compressional velocity, $V_P(90°)$ for the bedding-perpendicular compressional velocity, $V_{SH}(0°)$ for the horizontally polarized, bedding-parallel shear velocity, and $V_{SV}(0°)$ for the vertically polarized,