Elastic wave velocities under methane hydrate growth in Bentheim sandstones

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Abstract

Experimental acoustic laboratory measurement methods for hydrate-bearing poroelastic solid media are briefly reviewed. A measurement example using the Fourier spectrum method is given, for compressional and shear wave velocities in hydrate-bearing Bentheim sandstone.

1 Introduction

Methane gas hydrates exist in vast quantities beneath the ocean-bed, inland seas, and in the permafrost, and may potentially be used as an energy source [1,2,3]. The high energy density and the relatively low CO\textsubscript{2}-footprint (compared with coal) makes utilizing these hydrate resources highly relevant. Hydrate deposits stretch over large areas and monitoring hydrate deposits must therefore rely on remote monitoring methods. Acoustic parameters such as compressional ($c_P$) [4,5,6,7] and shear ($c_S$) wave velocities [6,7] and the compressional ($\alpha_P$) [7] and shear ($\alpha_S$) wave attenuation coefficients [7] are known to depend on the hydrate saturation ($S_H$). Acoustic methods have been pointed to as candidates for remote detection and monitoring of hydrate deposits [1].

The acoustic parameters $c_P$, $c_S$, $\alpha_P$ and $\alpha_S$ of hydrate-bearing poroelastic solid media do not only depend on $S_H$ but on many other factors, such as the free gas saturation ($S_g$), water saturation ($S_w$), measurement frequency, sediment composition and hydrate formation pattern. To understand field data such as acoustic well-log measurements [8,9], information on how all these listed factors affect the acoustic parameters is needed. Some of this information may be gained in the laboratory, where these factors may be adjusted and controlled [4,5,6,7]. Bentheim sandstone is a relatively homogeneous material and is fairly well described in the literature [23]. Thus, Bentheim sandstone was chosen in this study as the laboratory “host sediment” for hydrate to grow within.

Both sonic [6,7] (typically < 30 kHz) and ultrasonic [4,5,10,11,12] (typically >100 kHz) frequencies can be used to study elastic wave velocities in methane hydrate-bearing samples in the laboratory. For sonic frequencies, resonance methods have been used as measurement methods [6,7]. In studies using ultrasonic measurement frequencies, the time of flight to the first arrival of the acoustic pulse transmitted through the hy-
hydrate-bearing samples has been measured [4,5,10,11,12]. By using calibration rods of known dimensions and material parameters, the inherent time of flight in the transducers and in the electronics in the experimental setup can be subtracted [10]. Using this method, $c_P$ and $c_S$ have been measured during hydrate growth for hydrate-bearing samples in the laboratory.

At the first arrival of the signal, the signal strength is low and noise may affect the transit time measurements. There is no defined frequency in the transient of the signal and the method does not allow for attenuation measurements. When using shear wave transducers, both P-waves and S-waves are generated. It is apparent from for example Ref. [10] that P-wave components may interfere with the S-wave arriving later in the time trace. The accuracy of measuring the first arrival of the signal has been debated [13,14].

Another signal processing method is the Fourier spectrum method which has been used to measure elastic wave attenuation and velocity spectra [15,16]. The method relies on taking the Fourier transform of short pulses and does therefore not depend on accurate time domain measurements. In such methods where the frequency is well-defined, diffraction effects may also be corrected for [17,18].

In previous laboratory studies on hydrate-bearing poroelastic media, the hydrate formation pattern has received considerable attention [4,5,10,11,12]. The hydrate content has been estimated by interpreting the measured $c_P$ and $c_S$ using numerical models [19,20]. It has been investigated whether (i) hydrates form primarily within the pore fluid, or (ii) hydrates form and grow on individual grains, becoming a part of the frame, or (iii) hydrates form and grow at and around grain contacts, becoming part of the frame but also cementing the grains together. A general trend is that methane hydrates tend to form in the pore fluid in systems with high water content and adhere to the solid frame in systems where the water content is low [4,5,10,11,12]. Tohidi et al. [21] showed that methane hydrate forms primarily in the center of pores in “water-rich” systems initially containing bubbles of gas. Waite et al. [22] found that hydrate cements sediment grains in “gas-rich” systems initially containing discrete units of water. Apart from studies where synthetic hydrates (THF) have been formed, there appear to be few laboratory studies of the elastic properties of hydrate bearing consolidated poroelastic media; only one such laboratory study has been identified by the present authors [10].

In both consolidated poroelastic media [10] and unconsolidated [6,7,4,5,11,12] sand, a clear increase of both $c_P$ and $c_S$ as a function of $S_H$ has been found. This increase is found to be higher for unconsolidated sand. This indicates that different elastic properties should be expected for the same amount of methane hydrate depending on whether the reservoir sediment is a consolidated porous rock or unconsolidated sandy sediment. An example of such a consolidated porous rock is Bentheim sandstone, which has been used in this study.
2 Elastic wave velocities for hydrate-bearing Bentheim sandstone using the Fourier spectrum signal processing method

In an experimental study described by Sæther [17], acoustic properties of hydrate-bearing Bentheim sandstone was investigated e.g. using the Fourier spectrum signal processing method. Shear wave transducers were designed and constructed. The transducers were excited with short pulses and both P-waves and S-waves were measured. The measurement method, together with numerical simulation models for acoustic wave propagation in poroelastic media are are described in Ref. [17]. As an example of results, $c_P$ and $c_S$ are shown as a function of $S_H$ in Fig. 1, for a sample having an initial water saturation of $S_{w0} = 0.73$.

![Figure 1: Compressional, $c_P$, and shear $c_S$ wave velocities in a Bentheim sandstone with initial water saturation 0.73 during hydrate growth, $S_H$.](image)

The measurements show that as hydrates form, in the sandstone, the elastic wave velocities increase. A moderate increase is observed for $S_H < 0.2$. For $S_H > 0.2$, a more clear increase is seen in $c_P$ and $c_S$. Additional measurements and modeling results are presented and discussed in Ref. [17].

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