BENDER ELEMENTS IN DETECTING ACOUSTIC PROPERTIES OF GAS HYDRATE BEARING UNCONSOLIDATED SEDIMENTS

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ABSTRACT
The bender elements technique was introduced into measurement of ultrasonic waveforms of the gas hydrate-bearing unconsolidated sediments. Also, a new method (we called FFT-WT method hereafter), which combined Fast Fourier Transform (FFT) and wavelet transform (WT), is proposed to obtain both Vp and Vs of the hydrate-bearing unconsolidated sediments. The result shows that Vp and Vs increase rapidly versus hydrate saturations although they increase relatively slow in the range of saturation 25%~60%. It indicates that gas hydrate may first cement grain particles of the unconsolidated sediments, when hydrate saturation is higher, gas hydrate may contact with the sediment frame, or partly cementing sediment particles.

Keywords: bender elements; acoustic properties; wavelet transform; unconsolidated sediments

NOMENCLATURE
Ltt Tip-to-tip distance [m]
P Pressure [MPa]
tp Travel time of P-wave [s]
ts Travel time of S-wave [s]
t0p Inherent travel time of P-wave in transducers [s]
t0s Inherent travel time of S-wave in transducers [s]
Ta Inner temperature of the sample [°C]
Tb Surface temperature of the sample [°C]
Vp P-wave velocity [m/s]
Vs S-wave velocity [m/s]

INTRODUCTION
The attenuation of ultrasonic wave in the unconsolidated sediments is usually higher than that in consolidated sediments. In order to obtain both Vp and Vs of the hydrate-bearing unconsolidated sediments, various techniques including bender elements [1], resonant column [2], etc, are developed to measure acoustic properties of the hydrated samples. Bender elements are convenient shear wave transducers for optimal soil-transducer coupling and compatible operating frequency [3]. Using flat-plate P-wave transducers and S-wave bender elements, Yun et al. (2005) measured both Vp and Vs of the hydrate-bearing THF hydrates. In this study, we develop a new type of bender-extender elements to measure both Vp and Vs of the hydrate-bearing methane hydrates simultaneously.

BENDER ELEMENTS FOR METHANE HYDRATE-BEARING SEDIMENTS
Installation type
Bender elements consist of two sheets of piezoceramic plates rigidly bonded to a center shim of brass or stainless steel plate (Fig 1a). When the “cantilever beam” of the transducer is excited by an input voltage, it changes its shape and generates a mechanical excitation (Fig 1b), and then the signal transmits to the receiver bender element. The in-plane directivity of bender elements was explored by Lee and Santamarina (2005). The results show that amplitude of the signal is more pronounced when the installations of bender elements are parallel. The amplitude in the transverse configuration is about 75% of the amplitude at 0° in the parallel axes configuration.
which suggest the potential use of bender elements in a wide range of in-plane configurations besides the standard tip-to-tip alignment. In order to obtain good signal, we use the parallel installations in our experiments.

**Bender elements preparation**

Simultaneous measurements of compressional and shear wave velocity of methane hydrate bearing sediments using bender elements are explored. The apparatus is shown in Fig 2a. A high-pressure cell with a plastic inner barrel is used for simulating in situ pressure and temperature condition which is conducive for hydrate formation. Two platinum (Pt100) resistance thermometers with precision of \( \pm 0.1^\circ\text{C} \) are used to measure the temperature of the inside and surface of the sample. For more details of the apparatus, please see [4].

In the acoustic measuring system (Fig 2b), signal is generated, amplified and then transmitted by the source bender element. Because the mechanical excitation of bender element is transverse, the waveform received by the receiver bender element is mainly shear wave. In order to obtain both shear wave and compressional wave, a new kind of bender element is developed (Fig 3).

A photograph of the new bender elements is shown in Fig 3a. To overcome a high pressure environment, the bender elements are filled with phenolic resin and protected by stainless steel shell. The mechanical excitation of the new bender element is simply shown in Fig 3b. The cantilever beam is driven by two piezoelectric circles. When the excitation is generated, the cantilever beam will be distorted and the torsional vibration is occurred. At the same time, a small longitudinal movement is also occurred on the cantilever beam. In order to magnify the longitudinal movement, we add a longitudinal piezoelectric slice clinging to the bender elements. Therefore, there is also compressional wave in the integrative waveform (Fig 4). From the waveform, it’s easy to read the first arrival of shear wave. However, as the noise is largely, we develop a method called FFT-WT method to analysis the first arrival time of compressional wave (see section 2).

**Calibration**

Compressional and shear wave velocities are calculated with: 

\[
V_p = \frac{L_{tt}}{t_p-t_{0p}}, \quad V_s = \frac{L_{tt}}{t_s-t_{0s}},
\]

where \( L_{tt} \) is the tip-to-tip distance of two bender elements, \( t_p \) and \( t_s \) are travel times of compressional wave and shear wave in the sediments respectively, \( t_{0p} \) and \( t_{0s} \) are the inherent travel times of compressional wave and shear wave in the bender element transducers respectively.

Four different lengths of cylindrical Polyoxymethylene (POM) columns (Fig 5, Table 1) were used to calibrate \( t_{0p} \) and \( t_{0s} \) of the bender elements. The diameter of the POM columns are about 6cm, which is close to the diameter of samples (6.8cm). In each POM column, troughs are excavated at the two ends to conveniently place the bender elements’ cantilever beam (Fig 5). The waveform of the POM column is shown in Fig 6. It shows that it’s easy to read both arrival times of the P-
wave and S-wave using the new type of bender elements. For each POM column, the waveform measurement was repeated 5 times, with the average value as the arrival times of P-wave and S-wave. According to lengths and wave-arrival times of the four POM columns, we obtained the $t_{0p}$ and $t_{0s}$, which are 7.017us and 18.63us respectively (Fig 7). And the P-wave and S-wave velocities of the POM material are 2294.5m/s and 933.9m/s respectively, which is very close to the reported values [5]. The P-wave velocity is also close to the measured results by our flat-plate transducers reported by Hu et al. (2010), which is 2280m/s for POM-I and 2319m/s for POM-II.

Table 1. Parameters of the POM columns

<table>
<thead>
<tr>
<th>Number</th>
<th>Diameter (mm)</th>
<th>Length (mm)</th>
<th>Trough depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>POM-I</td>
<td>60.3</td>
<td>120</td>
<td>3.9~4.0</td>
</tr>
<tr>
<td>POM-II</td>
<td>60.3</td>
<td>150</td>
<td>3.9~4.0</td>
</tr>
<tr>
<td>POM-III</td>
<td>60.4</td>
<td>204</td>
<td>3.94</td>
</tr>
<tr>
<td>POM-IV</td>
<td>60.4</td>
<td>250</td>
<td>3.84</td>
</tr>
</tbody>
</table>

**FFT-WT METHOD**

Usually, there are two approaches to obtain the travel time of shear wave when using bender elements. In the first approach, the travel time can be directly read from the waveform of the receiver bender element. The characteristic point of wave’s arrival must be very markedly when using this approach. The second approach is based on detailed analysis of the waveform, such as the Dynamic Finite Element Analysis, Cross-Correction Analysis, Phase Velocity Analysis, Phase Sensitive Detection, etc. Because it’s easy to read the characteristic point of shear wave’s arrival in our experiments, we used the first approach to determine the travel time of shear wave. However, as shown in Fig 4, the acoustic noise of the samples is so large that it is nearly merged the small amount of compressional wave. In this condition, we develop a new analysis method, FFT-WT method, to determine the travel time of compressional wave.

The analysis process is as follows: (1) measuring the main frequencies of the bender element transducers; (2) choosing the compressional waveform (see Fig 4), make a Fast Fourier Transform (FFT) on the waveform, to obtain the main frequency of compressional wave; (3) making Wavelet Transform (WT) on the chosen compressional waveform, to obtain frequencies versus arrival time, from which the arrival time of compressional wave can be obtained. The detailed analysis process is given below.

Firstly, the frequencies of the bender element transducers are determined by admittance curves. The results indicate that the main shear frequency is 30KHz, while the main compressional frequencies are 75KHz, 125KHz, and 140KHz. Secondly, the frequency of compressional wave is analyzed by FFT (Fig 8). It shows that the frequencies of compressional wave mainly consist
of 122KHz and 73KHz. Thirdly, the chosen compressional waveform is analyzed by WT (Fig 9). With the frequency versus arrival time by WT, it shows that at about 96.1μs the frequency characteristics are the same with that analyzed by FFT. Thus, the travel time of compressional wave is 96.1μs with the above FFT-WT analysis.

Using above FFT-WT method, the travel time of shear wave can be also obtained. The results of Vs obtained using FFT-WT method are comparable with that measured by the first approach (in which the travel time of shear wave is read directly) (Fig 10), which indicates that the FFT-WT method is credible.

![Fig 10. Comparison of Vs determined by the direct method and the FFT-WT method](image)

**APPLICATION**

Methane hydrate was formed and then dissociated in the 0.09~0.125mm sands (with saturated water), during the process the acoustic velocities (Vp and Vs) of the samples are measured simultaneously with the new type of bender element transducers and analyzed with the FFT-WT method. Also, the water content, temperature, pressure of the porous media are measured (Fig 11). The results show that the time point of gas hydrates begin to form (or dissociate) detected by the acoustic velocities is the same with that detected by the temperature-pressure method, which indicates that the acoustic velocities measured by the new type of bender element transducers are very sensitive with gas hydrate formation and dissociation. Thus, it is effective for using the new type of bender elements in measuring both Vp and Vs of hydrate-bearing unconsolidated sediments under high pressure conditions.

The experimental result shows that the compressional (or shear) wave velocity measured in the hydrate-dissociation process is much lower than that measured in the hydrate-formation process at the same saturation degree (Fig 12). This may be caused by the influence of gas hydrates on the sediment frame. In the unconsolidated sediments, gas hydrates may act as a kind of cement. A small amount of gas hydrates may dramatically affects the acoustic velocities in this condition (Priest et al., 2005). During gas hydrate formation and dissociation in the unconsolidated sediments, the influences of gas hydrates on the sediment frame became smaller as time lapse. As a result, compressional (or shear) wave velocity of the hydrated unconsolidated sediments in the hydrate-dissociation process is lower than that in the hydrate-formation process.

With the average Vp (or Vs) of the compressional (or shear) wave velocities obtained in the two processes, we obtained the relationship between gas hydrate saturation and acoustic velocities of hydrate-bearing unconsolidated sediments. The result shows that Vp and Vs increase rapidly with hydrate saturations, although they increase relatively slow in the range of saturation 25%~60%. It indicates that gas hydrate may first cement grain particles of the unconsolidated sediments, when hydrate saturation is higher, gas hydrate may contact with the sediment frame, or continue cementing sediment particles.

![Fig 11. Changes of parameters during gas hydrate formation and subsequent dissociation](image)
CONCLUSIONS

In order to obtain both $V_p$ and $V_s$ of the hydrate-bearing unconsolidated sediments simultaneously under high pressure environments, a new type of bender element transducers has been introduced successfully. In the acoustic measurement, FFT-WT method was developed to analysis the compressional wave velocity. With the direct observation of $V_s$, it reveals the changes of both $V_p$ and $V_s$ during methane hydrate form and subsequently dissociate in porous sands. The results show that $V_p$ and $V_s$ increase rapidly with hydrate saturations, although they increase relatively slow in the range of saturation 25%–60%. It suggests that gas hydrate may first cement grain particles of the unconsolidated sediments, when hydrate saturation is higher, gas hydrate may contact with the sediment frame, or partly cementing the sediment particles.

REFERENCES

Fig 4. Integrative waveform of unconsolidated sediments by the new bender elements (tip-to-tip distance, 13cm)

Fig 6. Waveform of POM-I by bender element transducers

Fig 8. (a) chosen compressional waveform for FFT analysis; (b) main frequencies of compressional wave
Fig 9. WT analysis of waveform by bender element measurement