Journal of Natural Gas Science and Engineering 22 (2015) 90–97

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

Influence of heterogeneous hydrate distribution on the compressional wave velocity of hydrate-bearing sediment specimens

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ARTICLE INFO

Article history:
Received 13 September 2014
Received in revised form
14 November 2014
Accepted 18 November 2014
Available online 25 November 2014

Keywords:
Gas hydrate
Heterogeneous distribution
Compressional wave velocity
Porous media

ABSTRACT

This paper reports the results of a series of compressional wave velocity tests on specimens in which gas hydrate in the pores are substituted for iced pure water. In these specimens, ice is heterogeneously distributed by separating the ice-bearing sample into high- and low-saturation segments to simulate hydrate accumulation on one side of the specimen during synthesis of the hydrate-bearing sediment samples in laboratory. The length of high- and low-saturation segment was adjusted to simulate the different degrees of local accumulation of the synthesized hydrate-bearing sediment samples. The calculated saturation of the ice-bearing specimen from 15% to 40% with 5% saturation gradient was studied by the direct and indirect measurement methods. Ultrasonic measurements were performed to determine the compressional wave velocities, and results show that the heterogeneous distribution of ice in porous specimen remarkably influences the compressional wave velocity of the ice-bearing sample, especially for low-saturation samples. The compressional wave velocity increases with the increasing of the length of high saturation segment, and the maximum difference of the compressional wave velocity is up to 0.247 km/s (direct measurement) and 0.199 km/s (indirect measurement) at 30% calculated-saturation. This difference causes >20% uncertainty in the saturation of the ice-bearing sample using the Cementation Theory Model. Thus, the heterogeneous distribution of hydrate leads to a considerable measurement error for the compressional wave velocity of hydrate-bearing sediment sample. A larger error could occur during the estimation of hydrate saturation in the natural gas hydrate-bearing stratum, when the corresponding model of the hydrate saturation and compressional wave velocity corrected by the laboratory data are used to interpret the sonic logging data and seismic data.

1. Introduction

Gas hydrates are ice-like clathrate composed of water and gas molecules, which are mainly distributed in low-temperature and high-pressure conditions in nature, such as the permafrost area and continental margins (Englezos, 1993; Kvenvolden and Lorenson, 2011). Numerous studies have been focused on the potential of gas hydrates as energy resource and their important roles in submarine landslides and global warming (Kvenvolden, 1993b; Hovland and Gudmestad, 2001; Sloan, 1998; Kennett et al., 2003). The mining value of natural gas hydrate and its influence on submarine landslide depends on hydrate reserves. However, there are no direct methods available to measure gas hydrate reserves (Jose and Unberta, 2000). In order to ensure that the reserves of gas hydrate are in the sedimentary stratum, understanding the characteristics of the gas hydrate-bearing sediment is necessary (Kvenvolden, 1993a; Wait et al., 1999; Bagherzadeh et al., 2011). The compressional wave velocity (V_p) is one of the most important kinetic properties, which provides information on the lithology, saturation, and in-situ conditions of the gas hydrate-bearing sediment (Marisa and Michael, 2010; Carcione and Gei, 2004; Feng-Guang Li et al., 2011). Therefore, analyzing the variation in compressional wave velocity is an alternative method to estimate the amount of hydrate (Jose and Umberta, 2000). In addition, seismic techniques have been applied to survey marine gas hydrate depending upon the knowledge of compressional wave velocity.

A great many experiments have been conducted using synthetic gas hydrate-bearing sample to obtain compressional wave velocity. Waite et al. (Waite et al., 2004) employed ultrasonic technology to measure the compressional wave velocity of Ottawa sand samples, they found that, at 37% and 43% hydrate saturations, the P-wave velocities are 3.36 and 3.43 km/s, respectively. Jeffery et al. (Jeffrey

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http://dx.doi.org/10.1016/j.jngse.2014.11.021
1875-5100/

et al., 2005) employed resonant column apparatus to measure the compressional velocity of porous medium with sand, and found that, at 4.91% and 9.59% saturations, the P-wave velocities are 2.04 and 2.189 km/s, respectively. The measured data show that the maximum difference of V_p is 149 m/s, and the minimum difference is 50 m/s at 5% hydrate saturation discrepancy. Although the experimental materials and methods they employed were different, the data illustrate that the hydrate saturation is remarkably sensitive to the V_p and consequently the lager deviation of P wave velocity can cause a huge error of hydrate reserves in sedimentary strata. The saturation of the samples synthesized in laboratory is usually calculated from the consumed water or gas (Waite et al., 1999; Rydzy and Batzle, 2010; Li et al., 2011; Waite et al., 2004; Winters et al., 2007; Jeffrey et al., 2005, 2009; Wang Dong et al., 2008; Kwon and Cho, 2009; Zhang et al., 2011a,b). Nevertheless, the vast majority of studies did not consider the distribution of hydrate in the hydrate-bearing sediment sample. Several studies indicate that the use of pore water sample or wetted sands to synthesize hydrate can cause heterogeneous distribution of hydrate because of the moisture migration during the hydrate formation process (Makogon, 1981; Li et al., 2010; Waite et al., 2008; Zhang et al., 2011a,b; Huang and Fan, 2005; Winters et al., 2002). However, V_p is sensitive to the structure, porosity, mineral composition, and particle size of a sample (Helgerud et al., 1999; Dvorkin and Prasad, 1999); V_p changes with the heterogeneous distribution of hydrate. Different hydrate distributions can lead to different P-wave velocities of the hydrate-bearing sediment sample with the same saturation.

To obtain additional information about the influence of heterogeneous distribution of hydrate on the compressional wave velocity of the hydrate-bearing sediment samples, a series of experiments have been designed and conducted.

2. Experimental methods

As mentioned before, controlling the distribution of gas hydrate in porous medium is difficult. However, researches show that most of the hydrate-bearing sediment specimens synthesized in laboratory that the hydrate act as cement between sediment grains (Aman et al., 2013; Waite et al., 2004; Winters et al., 2004a; Winters et al., 2007), which are like the frozen soil (Matsumoto et al., 2013; Wang et al., 2008; Hagedorn et al., 2010). The compression deformation measurements at constant applied stress of methane (Stern et al., 1996) and of gas hydrate-bearing sediment (Parameswaran et al., 1989; Cameron et al., 1990) suggested that the strength of hydrate is very similar to ice. Most other researches also indicated that some physical properties of ice are similar to those of natural gas hydrate, and the properties of permafrost are often compared with those of hydrate-bearing sediments (Sloan, 1998; Miyairi et al., 1999). It's an efficiency way to use pure water ice to substitute gas hydrate in our experiments, for the ice-bearing samples are easily obtained in laboratory, and the distribution of ice in porous medium is relatively easy to control.

2.1. Experimental apparatus

Sample tubes made of stainless steel (72 mm in diameter, 150 mm in height, and 1 mm in wall thickness) were used to pack the samples. A ZBL-U520 non-metal acoustic detector was utilized to send and receive electric signals. Two piezo-electric transducers were fixed at the bottom and top of the test device. The top one was connected with a hand lever, which can move the transducer upward or downward to change the distance between the two transducers (Fig. 1). The frequency of the transducer was 250 KHz. The ultrasonic waves were sent and received using the transducers and the P-wave velocity was obtained by through-transmission. The sampling interval was 0.4 μs at 250 V excitation voltage. A refrigerator (−7 °C to −10 °C) was used to freeze the samples.

2.2. Experimental procedures

Our experiments were specifically designed to study the V_p changes with different prescribed heterogeneous distributions, which models the measurement with gas hydrate mainly accumulated at one end of the hydrate-bearing sediment sample (Makogon, 1981; Li et al., 2010; Huang and Fan, 2005; Winters et al., 2002). Measured samples are made of quartz sand with a grain size of 0.5 mm−1 mm. In order to obtain the porosity of the quartz sand sample, a precision electronic balance, a manual compaction meter and an evacuating device were employed. Firstly, Air-dried quartz sand was tamped in several layers within the sample tube by using the manual compaction meter until the quartz sand is full of the sample tube to form a dense solid cylindrical porous specimen; secondly, using the precision electronic balance to obtain the total mass of the quartz sand of the porous specimen, and this total mass of the quartz sand is the standard mass for all subsequent samples. The total volume of the porous specimen is calculated by the size of the sample tube; thirdly, in order to ensure the specimen is completely saturated, the porous specimen was put into the tank of the evacuating device which is full of distilled water to inundate the specimen and eliminate the air from the tank for twenty-four hours; at last, the total mass of saturated specimen was measured by the precision electronic balance, the pore water in the porous specimen is also obtained by using the total mass of the saturated specimen to minus the total mass of the quartz sand. The volume of the pore space is obtained by calculating the volume of the pore water, the porosity of the sample also can be obtain and the final porosity we calculated is 38.2%.

To distinguish the saturation in the experiments, the average saturation of the whole specimen was considered the calculated saturation. In the same calculated saturation condition, the samples

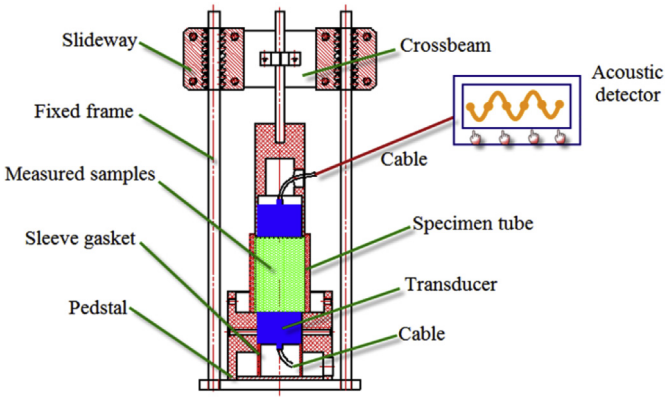

Fig. 1. Schematic of the measurement apparatus.

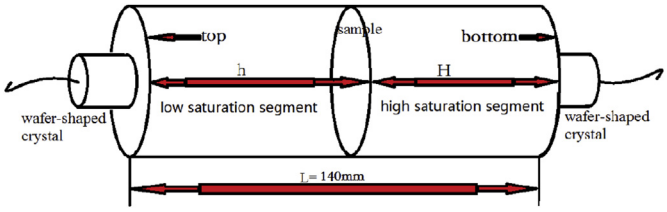

Fig. 2. Schematic of composition and measurement of the sample.