Marine and Petroleum Geology 25 (2008) 884–895

Contents lists available at ScienceDirect

Marine and Petroleum Geology

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

Mechanical and electromagnetic properties of northern Gulf of Mexico sediments with and without THF hydrates

J.Y. Lee [a,1], J.C. Santamarina [a,2], C. Ruppel [b,*]

[a] School of Civil and Environmental Engineering, Georgia Institute of Technology, 790 Atlantic Avenue NW, Atlanta, GA, USA
[b] U.S. Geological Survey, 384 Woods Hole Road, Woods Hole, MA 02543, USA

ARTICLE INFO

Article history:
Received 31 January 2007
Received in revised form 12 October 2007
Accepted 14 January 2008

Keywords:
Gulf of Mexico
Gas hydrate
Permittivity
Conductivity
Fabric
Stiffness
Seismic velocity

ABSTRACT

Using an oedometer cell instrumented to measure the evolution of electromagnetic properties, small strain stiffness, and temperature, we conducted consolidation tests on sediments recovered during drilling in the northern Gulf of Mexico at the Atwater Valley and Keathley Canyon sites as part of the 2005 Chevron Joint Industry Project on Methane Hydrates. The tested specimens include both unremolded specimens (as recovered from the original core liner) and remolded sediments both without gas hydrate and with pore fluid exchanged to attain 100% synthetic (tetrahydrofuran) hydrate saturation at any stage of loading. Test results demonstrate the extent to which the electromagnetic and mechanical properties of hydrate-bearing marine sediments are governed by the vertical effective stress, stress history, porosity, hydrate saturation, fabric, ionic concentration of the pore fluid, and temperature. We also show how permittivity and electrical conductivity data can be used to estimate the evolution of hydrate volume fraction during formation. The gradual evolution of geophysical properties during hydrate formation probably reflects the slow increase in ionic concentration in the pore fluid due to ion exclusion in closed systems and the gradual decrease in average pore size in which the hydrate forms. During hydrate formation, the increase in S-wave velocity is delayed with respect to the decrease in permittivity, consistent with hydrate formation on mineral surfaces and subsequent crystal growth toward the pore space. No significant decementation/debonding occurred in 100% THF hydrate-saturated sediments during unloading, hence the probability of sampling hydrate-bearing sediments without disturbing the original sediment fabric is greatest for samples in which the gas hydrate is primarily responsible for maintaining the sediment fabric and for which the time between core retrieval and restoration of in situ effective stress in the laboratory is minimized. In evaluating the impact of core retrieval on specimen properties, it is also important to consider how far removed hydrate-bearing samples are from hydrate stability conditions.

1. Introduction

The impact of ice on the physical properties of host sediments has long been a subject of intense research in the geotechnical literature, but only in recent years has there been a major focus on understanding the properties of sediments containing another frozen substance – gas hydrate (e.g., Francisca et al., 2005; Yun et al., 2006a,b, 2007). Gas hydrate consists of a hydrogen-bonded water lattice surrounding guest gas molecules of low molecular weight. Methane is the most common guest molecule, but higher order hydrocarbons, hydrogen sulfide, and carbon dioxide also form gas hydrates under appropriate pressure and temperature conditions. Compared to ice, which persists only in permafrost regions, gas hydrates are far more widespread, occurring in both permafrost sediments to depths of ~1 km and deep marine sediments at water depths greater than ~300 m on the world's continental margins.

Scientific motivations for studying gas hydrates include their potential as an unconventional hydrocarbon resource, their possible role in global climate change, and/or their connection to seafloor geohazards such as slope failures. Laboratory studies comparing the geotechnical and geophysical properties of natural sediments both with and without gas hydrate advance our understanding of these issues in several ways. The resulting data could be used to calibrate relationships between geophysical parameters and gas hydrate saturation. Such relationships can be applied to evaluate the impact of hydrate formation and

* Corresponding author. Tel.: +1 508 457 2339.
E-mail addresses: jylee@kis.kigam.re.kr (J.Y. Lee), carlos@ce.gatech.edu (J.C. Santamarina), cruppel@usgs.gov (C. Ruppel).
[1] Present address: Korean Institute of Geoscience and Mineral Resources KIGAM, South Korea.
[2] Tel.: +1 404 894 7605.

0264-8172/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.marpetgeo.2008.01.019

dissociation on the mechanical behavior of hydrate-bearing sediments and to assess how coring and drilling of hydrate-bearing sediments affect their properties, an important issue for evaluating production strategies.

In this paper, we report on the geophysical and geotechnical properties of natural sediments obtained during conventional coring of boreholes drilled in potential gas hydrate zones in the northern Gulf of Mexico. The specimens were studied in both their undisturbed and remolded states, with and without synthetic hydrate. Results provide insight into processes accompanying the nucleation and growth of gas hydrate, new approaches to estimating hydrate saturation using geophysical observables, and the impact of coring on hydrate-bearing sediments.

2. Study site

Specimens for this study were obtained during 2005 drilling by the ChevronTexaco Joint Industry Project (JIP) on Methane Hydrates at two sites in the northern Gulf of Mexico (Fig. 1). The northern Gulf of Mexico seaward of the shelf break and north of the Sigbee escarpment is a complex passive margin setting characterized by a variable-thickness sedimentary section overlying deformed, allochthonous salt deposits. Salt dissolution and withdrawal have led to the formation of sediment-filled mini-basins, which mostly occupy bathymetric lows, surrounded by bathymetric highs that correspond to subsurface salt (e.g., Diegel et al., 1995; Peel et al., 1995). Faults that accommodate the rising salt play an important role in focusing fluid flow at the edges of mini-basins. Such faults often channel thermogenic gases upward toward the seafloor from deep hydrocarbon reservoirs (e.g., Sassen et al., 1999), leading to gas hydrate formation in shallow subseafloor sediments and occasionally at the seafloor when appropriate pressure–temperature conditions are encountered by the ascending fluids. At other locations, including the sites discussed in this paper, biogenic gas prevails (Lorenson et al., 2008). This gas may either represent migrated, older gas that has accumulated within the deeper sedimentary section or possibly biogenic gas generated in situ.

The two focus sites for the 2005 JIP drilling were Atwater Valley lease block 13 (AT13 at 28°N, 89.289°W and water depth of 1291 m) and Keathley Canyon lease block 151 (KC151-3 at 26.823°N, 92.987°W and water depth of 1323 m). Detailed descriptions of these sites are given elsewhere (e.g., Hutchinson et al., 2008; Wood et al., 2008), and initial results gleaned from drilling are detailed by Claypool (2006). The Keathley Canyon site lies on a bathymetric high close to a fault system on the southeastern side of the so-called Casey mini-basin, where a bottom simulating reflector (BSR) has been imaged (e.g., Hutchinson et al., in press). Drilling at the Atwater Valley site primarily focused on seafloor features identified before the cruise as possible gas hydrate mounds, but also included some reference sites outside the mound area. The AT13 sample analyzed in this paper was obtained at one of the reference sites. The KC and AT drilling sites represent different endmembers in the spectrum from a low flux gas hydrate site characterized by a BSR (KC151) to high flux site with punctuated fluid flow at the gas hydrate mounds (AT13). At the same time, the sites also lie at approximately the same water depth (hydrostatic pressure), which facilitates comparison of the hydrate stability conditions.

3. Sample description

Geotechnical and physical property results obtained on conventional (Yun et al., 2006a) and pressure cores (Yun et al., 2006b) recovered at the KC151 and AT13 sites have been previously documented in the literature. Data reported by Yun et al. (2006a) indicate that the specific surface S_a of the sediments at these sites varies from 62 $m^2 g^{-1}$ to 143 $m^2 g^{-1}$ in samples obtained from the uppermost ~150 m of sediments at AT13 and ~350 m at KC151. Such a high S_a suggests that the sediments are clay-dominated and likely indicates the presence of illite or/and montmorillonite. Based on the liquid limit LL (74.9–77.0 at AT13 and 51.2–66.6 at KC151) and the plastic limit PL (27.0–30.5 at AT13 and 20.7–22.7 at KC151), these sediments are classified as inorganic clays with high plasticity, corresponding to designator CH in the Unified Soil Classification System (Yun et al., 2006a). Results obtained more recently by Winters et al. (2008) on core materials from some of the same boreholes do not alter the conclusions published by Yun et al. (2006a) or the information summarized here.

For this study, we used whole-round samples obtained at 0.65 m below seafloor (mbsf) at AT13 (core AT13-1H) and 275 mbsf at KC151 (core KC151-3-19H). Both specimens were retrieved using the Fugro hydraulic piston corer. Conventional cores acquired at depths closest to the depths of our specimens have S_a of 94.2 $m^2 g^{-1}$ and 119.9 $m^2 g^{-1}$ and water content of 123.9% and 36.1% for AT13 and KC151, respectively (Yun et al., 2006a). Reported pore fluid salinities at these depths are 3.5% by weight at AT13 and between

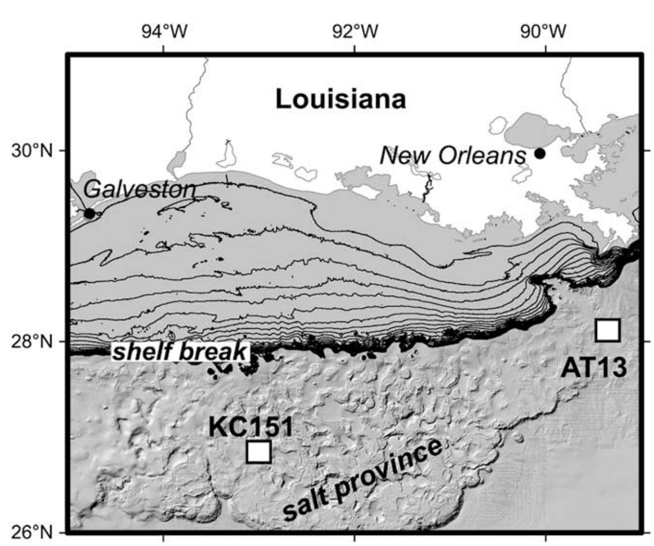

Fig. 1. Locations at which cores used in this study were recovered during 2005 DOE–JIP drilling in the northern Gulf of Mexico salt province.

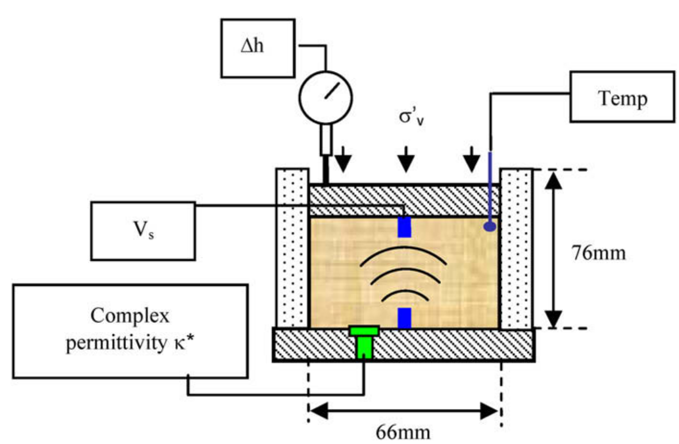

Fig. 2. Schematic of oedometer cell, sensors, and peripheral electronics. Temperature and complex permittivity sensors provide local measurements that average over only a small volume adjacent to the sensor. In contrast, the shear wave velocity represents a bulk, height-averaged value, primarily along the sample's axis.