Methane Hydrates: Sampling and Pressure Core Technology

Les Hydrates de Méthane : Echantillonnage et la Technologie de Pression de Noyau

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ABSTRACT: Gas expansion in sediments mobilizes capillary forces that can cause extensive destructuration during sampling and core recovery. The situation is aggravated in marine and permafrost hydrate-bearing sediments as hydrate dissociation experiences a volume expansion of ~172 times. Pressure core technology prevents hydrate dissociation: unique samplers lock-in the in-situ fluid pressure and subsequent sediment characterization takes place without ever depressurizing the specimen. While the fluid pressure remains within the stability field, specimens experience changes in effective stress. Samplers and test chambers must be carefully designed, and test protocols meticulously executed to obtain reliable properties for analyses and design. Lessons learned in geotechnical engineering and experimental results obtained with hydrate-bearing sediments help advance pressure core sampling and testing technology. The technology has been deployed to study hydrate-bearing sediments in the Gulf of Mexico (USA), Krishna-Godavari Basin (India), Ulleung Basin (S. Korea), and Nankai Trough (Japan).

RÉSUMÉ : L'expansion du gaz dans les sédiments mobilise les forces capillaires qui causent la destructuration du sol pendant l'échantillonnage et la récupération de la carotte. La situation est aggravée dans les sédiments marins et de pergélisol car la dissociation des hydrates, dans ce cas-ci, connaît une expansion de volume de ~ 172 fois. La technologie du noyau de pression empêche la dissociation d'hydratés: les échantillonnages sont uniques et verrouillent la pression interne du fluide, et la caractérisation subséquente des sédiments s'effectuent sans dépressuriser l'échantillon. Alors que la pression du fluide reste dans le champ de stabilité, les spécimens subissent des changements dans la pression effectif. Les échantillonneurs et les chambres d'essai doivent être soigneusement conçus et les protocoles de test doivent être minutieusement exécutés pour obtenir des propriétés fiables d'analyse et de désign. Les leçons tirées de l'ingénierie géotechnique et les résultats expérimentaux obtenus avec des sédiments d'hydrates contribuent à l'avancement de la technique de prélèvement et d'essai de noyaux de pression. La technologie a été déployée pour étudier les sédiments avec hydratants dans le Golfe du Mexique (USA), le bassin Krishna-Godavari (Inde), le bassin d'Ulleung (Corée du Sud) et Nankai Trough (Japon).

KEYWORDS: methane hydrates, natural sample testing, sampling, pressure core technology.

1 INTRODUCTION

Sample disturbance during drilling, cutting and extraction limits geotechnical engineering analyses and design. Sampling implies the loss of effective stress and associated sediment destructuration (Santagata and Germaine 2005). When sampling changes the sediment structure, the classical re-loading techniques will not reproduce the original stress-strain response (Ladd and Foott, 1974, Tanaka 2000, Tanaka et al. 2002, Hird and Hajj 1995).

Methane hydrate is stable at high water pressure and low temperature. During sampling, hydrate expands 172 times upon dissociation and causes massive distructuring of the host sediment.

The proper design of sampling equipment and procedures plays a critical role on the accuracy of measured properties. This article reviews sampling disturbance and describes current sampling and characterization technology for hydrate-bearing sediments.

2 NEAR SURFACE SEDIMENTS - SAMPLER

Sampling disturbance depends on sediment type, cementation, particle diameter, in-situ conditions and sampling tools and protocols. Additional disturbance takes place during sample handling and transportation from the site to the laboratory, extrusion of the sample from the sampler, and trimming to adapt samples to test cells (Baligh et al. 1987, Ladd and DeGroot 2003).

Disturbance alters the stress history and compressibility (typically: higher recompression index, reduced pre-consolidation stress and lower virgin compression index), lowers the initial stiffness and increases the strain at peak strength (Budhu and Wu, 1992; Clayton and Siddique, 1999; Long, 2002; Long, 2003; Safaqah and Riemer, 2006; Siddique et al. 1999).

The sampler geometry has a major impact on sample quality. Figure 1 shows a typical sampler. The dimensionless ratio "inside clearance" C_i affects lateral relaxation and the mobilization of wall friction, the "outside clearance" C_o determines the outside friction, and the "area ratio" C_a captures the displaced volume relative to the sampled volume. Disturbance decreases with smaller area ratios C_a and with sharper cutting edges (Clayton and Siddique 1999, Horng et al. 2010, Long 2002, DeGroot 2003). While small area ratios are preferred, values often exceed C_a=30% due to mechanical constraints (Clayton et al. 1995).

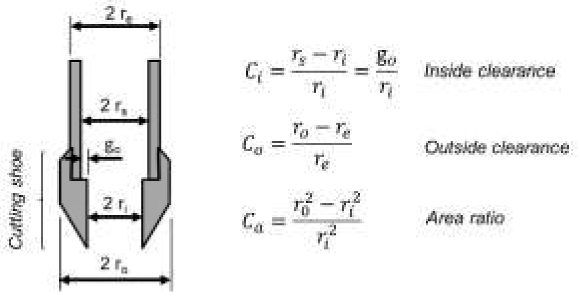

Figure 1. Sampler geometry and dimensionless ratios.

3 PRESSURE CORES: MARINE SEDIMENTS

Cores recovered from sediments subjected to high in-situ water pressure can experience severe disturbance if gas exsolution or hydrate dissociation takes place. In this case, specimens must be recovered using pressure core technology.

A typical drilling and coring system for deep marine sediments consists of a drive mechanism, the autoclave section, a plastic liner with a catcher and a valve to maintain the internal water pressure (Figure 2-a). The Fugro Pressure Corer FPC uses a percussion system to drive the sampler, while the HYACE rotary corer relies on a mud motor (Kolk and Wegerif 2005, Huey 2009). The specimen slides into the plastic liner and is trapped by the catcher; then, the tool is lifted from the recovery hook. The specimen remains housed inside the autoclave section and the ball valve closes to maintain internal fluid pressure. Pressure cores have been recovered from hydrate-bearing sediments in China, India, Japan, Korea, Taiwan and USA (Koh et al. 2012, Schultheiss et al. 2009). Currently, the probability of successful recovery is 60-70% (Yamamoto et al. 2012).

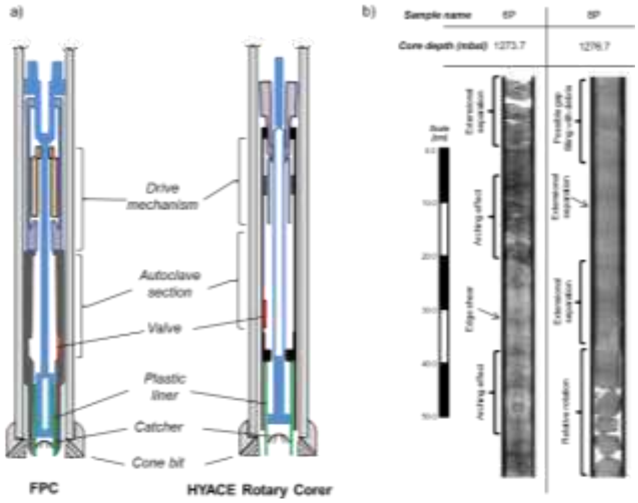

Figure 2. Pressure corers: (a) Fugro Pressure Corer and HYACE (modified from Peuchen 2007, Kolk and Wegerif 2005, iodp.org). (b) Typical X-ray images from the pressure cores recovered at the Nankai Trough, Japan (with permission JOGMEC). Samples were obtained using a 53.6 mm (ID) liner and 51.4 mm cutting shoe (JOGMEC corer).

Pressure core sampling technology must be complemented with characterization tools that can test the specimen at the in-situ fluid pressure, without ever depressurizing it. We developed a comprehensive set of pressure core characterization tools PCCTs to subsample core segments and to measure complementary information relevant to science and engineering, with emphasis on parameters used in hydro-thermo-mechanical analyses: oedometric compressibility, hydraulic conductivity, S- and P-wave velocity, strength, electrical conductivity, thermal conductivity, bio-activity and cultures (Figure 3 - Yun et al. 2006, Santamarina et al. 2012).

All tools satisfy common designed objectives: simple and robust systems, portable components for fast deployment, modular design (any two tools/chambers can be readily coupled through an identical flange-clamp system), standard dimensions and parts for economic construction and maintenance, rust-resistance for seawater environment (all devices are made of stainless steel 316), 35 MPa fluid pressure rating and ability to operate at 21 MPa, and are capable to impose effective stress when physical parameters are effective stress dependent.

Moreover, all tools are safe for the monitoring hydrate dissociation and gas production during controlled depressurization, heating or fluid exchange (such as with liquid CO2). Other tools have been developed for X-ray imaging (Schultheiss et al. 2009), triaxial testing (Yoneda, J. et al 2015) and resonant column testing (Priest et al 2015).

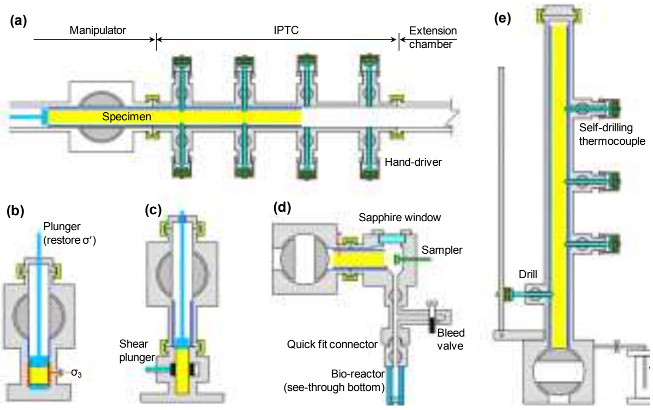

Figure 3. Pressure core characterization tools PCCTs. (a) Instrumented pressure testing chamber with P-T control. (b) Effective stress chamber with σ'-P-T control. (c) Direct shear chamber with σ'-τ-P-T control. (d) Controlled depressurization chamber for sediment preservation and gas production. (e) Bio-sampler for multiple bio-reactor chambers. Scale: the outside diameter of the large ball valve shown in all devices is OD = 220 mm (Santamarina et al. 2012).

4 DEEP SEDIMENTS: EXPANSION vs. PLUGGING

Even the best quality pressure cores share all other sampling difficulties listed above for near surface sediments. X-ray images of pressure cores inside the autoclave readily show sampling effects such as: edge shear, friction, sample expansion, core rotation and shear, gaps or extensional separations (Figure 2-b).

Marine operations are costly and technically cumbersome. Long cores are preferred to reduce tripping time (some cores exceed 10 m). However, the large internal clearance that is required to reduce side friction and plugging allows for stress relaxation; the transient pressure drop inside the core may trigger gas exsolution or hydrate dissociation.

Two extreme conditions are analyzed next. First, a cemented core is allowed to expand freely within the sampler (potential case in high hydrate saturation specimens). Second, an un-cemented sediment mobilizes friction as it slides into the sampler (potential case in low hydrate saturation formations).

4.1 *Cemented Sediments: Radial Expansion*

Rotary coring is preferred to advance the sampler in high hydrate saturation cemented sediments. The cutting shoe diameter is smaller than the sample liner inside the autoclave, the effective lateral stress is released and the core expands. The optimal radial gap/clearance $g_o=r_s-r_i=C_i r_i$ between the cutting shoe and the sampler liner has to be large enough to allow the core to enter the sampler, but small enough to limit relaxation.

Let's consider the core expansion in the radial direction caused by a stress change $\Delta P_{ext}=\sigma'_{lat}-p$ where σ'_{lat} is the original lateral effective stress and p is the final confinement. The sediment will experience a radial expansion:

$$u_r|_{sed} = \frac{r_i}{2\ G_{sed}}(\sigma'_{lat} - p) \qquad (1)$$

where G_{sed} [Pa] is the sediment shear stiffness and r_i [m] is the initial core radius. The sampler will react and apply some confinement p>0 as soon as the relaxing sediment engages the sampler wall. A pressure p will expand the sampler radially (Figure 4):

$$u_r|_{sampler} = \frac{r_s^2}{E_{sampler}\ t}\ p \qquad (2)$$

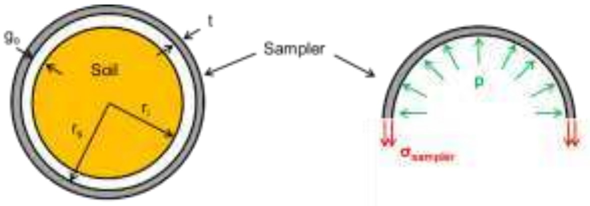

Figure 4. General geometry for the analysis of the sampler-sediment interaction. Sediment expansion against the sampler.

where $E_{sampler}$ [Pa] is the Young modulus of the material the sampler is made-of, t [m] is the sampler wall thickness and r_s+t/2≈r_s is the sampler mean radius (Note: if a plastic liner is used, these parameters correspond to the liner).

Compatibility of deformations requires that $u_r|_{sed}=g_o+u_r|_{sampler}$. Then, the confining pressure the sampler exerts on the sediment is:

$$p=\frac{\frac{\sigma'_{lat}}{G_{sed}}-2\frac{g_o}{r_i}}{2\frac{G_{sed}}{E_{sampler}}\frac{r_s^2}{t\ r_i}+1}G_{sed}\geq 0 \qquad (3)$$

4.2 *Non-Cemented Sediments: Plugging*

The sampler may plug and limit the length of recovered sediment (Paikowsky 1990, Paikowsky and Whitman 1990, Randolph et al. 1991). Plugging can develop under all types of driving conditions (Iskander 2011), and the recovered sample is severely affected (Hvorslev 1949, La Rochelle et al. 1981).

Un-cemented sediments yield and "flow" inside the sampler, fill the gap g_o, and develop friction against the sampler wall as the sediment enters the sampler. Then, the length of the recovered core will be a function of core-sampler frictional resistance and the end bearing capacity at the front of the corer. When these two forces are equal, the sediment ahead of the sampler displaces away from the coring tool and stops sliding into the sampler.

The vertical equilibrium of a sediment slice thickness dz is (Figure 5; see also Randolph et al. 1991 – Note: the coordinate z refers to sediment depth inside the sampler):

$$\frac{\partial\sigma'_z}{\partial z}\ d_z\pi\ r_s^2=2\ \pi\ r_s\ \mu\ k\ (\sigma'_z\ d_z)+\pi\ r_s^2\ \gamma\ d_z \qquad (4)$$

where σ'_z [kPa] is the vertical effective stress in the sediment at a depth z within the sampler, γ [kN/m^3] the sediment unit weight, and r_s [m] the sampler radius.

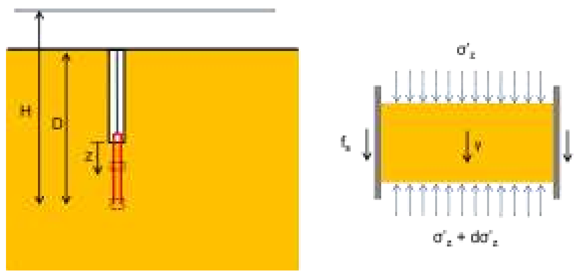

Figure 5. Non-cemented sediments: Forces involved in plugging.

The wall friction $f_s=\mu\cdot k\cdot\sigma'_z$ is a function of the friction coefficient μ between the sediment and the sampler, and the horizontal-to-vertical effective stress ratio k within the sample. The solution of the differential equation 4 is:

$$\sigma'_z=\frac{\gamma\ r_s}{2\ \mu\cdot k}\left[e^{\left(\frac{2\ \mu\cdot k\ z}{r_s}\right)}-1\right] \qquad (5)$$

The maximum length L of core recovered when plugging takes place corresponds to the depth z=L when the vertical stress at the base of the sample equals the bearing capacity $q_{ult}=\gamma DN_q$ where D is the sampling depth (Figure 5). For deep cores D/r_s>>1,

$$L=\frac{r_s}{2\ \mu\cdot k}\ ln\left(\frac{2\ \mu\cdot k}{r_s}D\ \ N_q\right) \qquad (6)$$

The stress ratio k ranges from ko at-rest to the active earth pressure coefficient ka. The factor μ·k varies in a relative narrow range for typical sediment friction angles, and a value of μ·k= 0.11-to-0.17 can be adopted for preliminary analyses.

5 GUIDELINES FOR SAMPLING TOOL DESIGN

The previous analyses support the development of mechanically robust guidelines for the design of coring tools.

5.1 *Optimal Gap*

The inside clearance is C_i=0-to-0.5% for short samples and for normally consolidated or slightly over-consolidated clays (prevents tension above the tip); a larger clearance C_i= 0.75-to-1.5% is recommended for over-consolidated clays and long samples (Hvorslev 1949, La Rochelle et al. 1981, Clayton et al. 1995, Clayton and Siddique 1999; see also ISSMEFE Report of the Subcommittee on Problems and Practices in Soil Sampling). The thin-wall sampler described in ASTM D6519-08 has an inside clearance C_i= 1%.

Equation 3 allows us to compute the inside clearance coefficient $C_i = g_o/r_i$, (Figure 1) for a given degree of "acceptable lateral relaxation" $\beta=(\sigma_{lat}-p)/\sigma_{lat}$ for high hydrate saturation sediments (Note: complete core relaxation p→0 corresponds to β=1):

$$C_i=\frac{\sigma'_{lat}}{G_{sed}}\left[\frac{\beta}{2}-(1-\beta)\frac{G_{sed}}{E_{sampler}}\frac{r_s}{t}\right] \qquad (7)$$

Given the clearances in standard practice summarized above, high hydrate saturation sediment cores will expand and yield long before they react against the sampler wall. For example, let's consider cores recovered from the Nankai Trough, Japan, and typical hydrate-bearing sediment properties. Results plotted in Figure 6 suggest the loss in confinement and yield. In fact, X-ray images in Figure 2-b show the sediment completely detached from the sampler wall when layers have high hydrate saturation; conversely, the sediment fills the gap in hydrate-free layers. The insert in Figure 6 shows that the plastic liner p-ε curve plots outside the acceptable core deformation range.

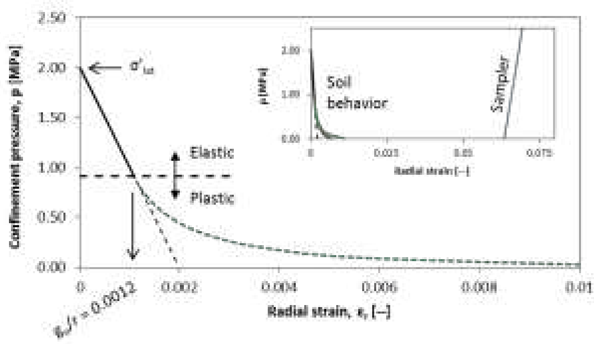

Figure 6. Core relaxation inside plastic liner sampler – Case: Hydrate-bearing sediments from the Nankai Trough. Insert: large scale to supperimpose the liner response. The values used for this computation are: σ'_{lat}= 2 MPa; G_{sed}= 500 MPa; φ= 30°; r_i= 25.2 mm; r_s= 26.8 mm; t= 3 mm; $E_{plastic}$= 4 GPa.

4.2 *Maximum Recoverable Length (Un-Cemented Sediments)*

Equation 6 indicates that the maximum core length recovered at plugging L/r_s increases with depth D and friction angle and may reach $L/r_s \rightarrow$ ~40-50 for deep sediments. In shallow sediments, samplers plug when L/r_s=10-to-20 in clayey sediments, and L/r_s=25-to-35 in sandy sediments, which compares well with reported values (see also Paikowsky and Whitman 1990).

Consider the case of marine sediments: a sampler radius r_s= 25mm and operating at depths of 300 mbsf can recover a maximum length L_{max}= 60 cm of un-cemented sediments. On the other hand, we can recover long cemented hydrate-bearing sediment cores - as long as un-cemented layers do not plug the sampler.

6 CONCLUSIONS

Sampling and coring alter the measured sediment properties. Gas exsolution and hydrate dissociation exacerbate sampling disturbance. Pressure core sampling and testing technology implements core recovery and testing without ever causing fluid depressurization or phase transformation.

Still, mechanical disturbance remains. The analysis of lateral stress relaxation and plugging allows us to develop robust guidelines for the design of coring equipment to sample hydrate-bearing sediments.

Results show that typical guidelines developed for geotechnical practice have a significant gap and result in full relaxation of hydrate-bearing sediments with high degrees of hydrate saturation. A lower clearance factor Ci=$g_o/r \approx$0.1% limits core expansion. Yet, frictional resistance must not cause the plastic liner to buckle or crash longitudinally.

Plugging should be expected with all samplers. The recoverable length can exceed L/r_s~30 in deep sediments. Sediment-sampler interaction parameters affect the predicted plugging length. The friction factor $\mu \cdot k$ varies in a narrow range for most sediments. Preliminary analyses can adopt a value $\mu \cdot k$= 0.11-0.17.

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