MANAGING IMPACTS OF DEEP SEA RESOURCE EXPLOITATION

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Complete geo-mechanical properties of gas hydrate bearing sediments from in situ geotechnical measurements

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Scope of the report

The present report aims at providing details about the overall approach, tool and processing techniques deployed to determine geo-mechanical properties of gas hydrate-bearing sediments from in situ geotechnical measurements carried out in the Black Sea.

1 Introduction

Understanding the mechanical behaviour of gas hydrate-bearing sediments is of fundamental importance in assessing the potential for submarine slope instability as a result either of exploration or exploitation activity, or of environmental change (Clayton et al., 2008; Uchida et al., 2012). This requires quantification by a reasonably good number of different geotechnical parameters (Yamamoto et al., 2015). Despite recent developments of pressure-core sampling and testing systems the properties of undisturbed, natural gas hydrate-bearing sediments remain particularly challenging to quantify (Dai et al., 2014; Priest et al., 2015). In situ testing is an alternative and cost effective means of acquiring large amount of data, especially when high-quality samples are difficult to obtain for laboratory tests (Robertson, 2012). Piezocone test is particularly well-suited for this purpose as three independent measurements are obtained with depth by a single sounding. These measurements include the tip resistance, the sleeve friction and the penetration pore pressure, from which correlations have been developed for evaluating geotechnical parameters of different soil types. Sultan et al., (2007, 2010) have shown that piezocone sounding allows the detection of gas hydrates, based on notable increases in tip resistance and sleeve friction above values commonly indicative for the presence of sand. Recent piezocone soundings carried out by Ifremer during the GHASS cruise (September 2015) in the Black Sea revealed similar features at a site where gas hydrates were recovered by piston coring. The present report is built upon this discovery and on comparison of similarities and differences with sediments without hydrates. This serves as a basis to derive geo-mechanical properties of gas hydrate-bearing sediments, keeping in mind that selective sampling and laboratory testing remains required to carry out statistical studies enabling new or improved sets of correlation to be developed.

2 In situ geotechnical sounding with the PENFELD penetrometer

2.1 Details of the Penfeld penetrometer

The Penfeld penetrometer is a seabed rig developed by Ifremer to ensure piezocone penetration at a constant rate of 2 cm/s down to 30 m below seabed (Sultan et al., 2007, Figure 1). The piezocone continuously measures the tip resistance (q_c), sleeve friction (f_s) and penetration-induced pore pressures (Δu_2) (Figure). The cone has a projected area of 10 cm ² with an apex angle of 60°. The friction sleeve is 15 cm long and 3.6 cm in diameter.

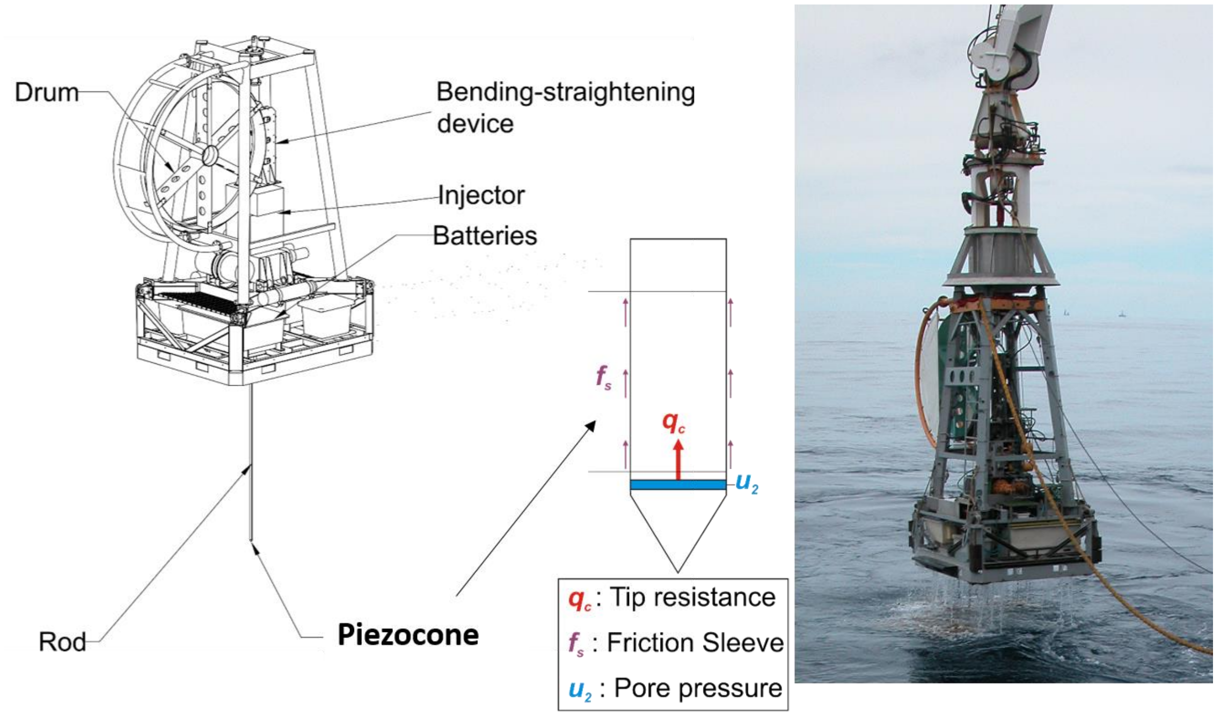

Figure 1: Illustration of the Penfeld penetrometer used to carry out piezocone sounding.

Two different load cells are used to measure the tip resistance and sleeve friction. Pore pressure is measured with a differential pressure sensor located immediately behind the cone (u_2 position). The characteristics of the three different sensors are presented in Table 1.

Because the piezocone is compensated so that the inside pressure is equal to the hydrostatic water pressure outside, excess pore pressure values (Δu_2) allow to obtain values of corrected tip resistance , q_t, using the following equation:

$$q_t = q_c + (\Delta u_2 - u_h)$$

Where u_h is the hydrostatic water pressure.

Piezocone	Sensor	Measurement range	Accuracy
E3P3	Tip resistance	20 kN	0.1 kN
	Sleeve friction	10 kN	0.05 kN
	Pore pressure	7 MPa	0.0175 MPa

Table 1 : Summary of the characteristics of the sensors of piezocone E3P3.

2.2 Piezocone soundings in the Black Sea

A total number of 43 piezocone soundings have been completed with the Penfeld penetrometer in the Romanian sector of the Black Sea (Figure 2) during the GHASS cruise. Twenty one of them were located deeper than 721 m water depth which corresponds to the theoretical limit of the methane hydrate stability zone, considering sea bottom temperature and salinity of 9.1°C and 22.3 g/L, respectively (Bialas et al., 2014). All these 21 sites were also located above a bottom simulating reflector mapped by Popescu et al., (2006) and considered as an additional evidence for the possible occurrence of gas hydrates in sediments (Figure 2). Despite the number of sites investigated with the Penfeld penetrometer, the present report will focus on the single site, GAS-CPTu-07-S04, where peculiar piezocone readings could have been unambiguously reconciled with direct observations of gas hydrates in core GAS-CS14 (see location in Figure 2). This site is located by 729 m water depth, at the top of a bathymetric high running N-S along a distance of 3 km with a maximum height above the surrounding area of about 50 m (Figure 2).

Few gas hydrates nodules were observed from 1 m to 4 m depth in core GAS-CS14 (Figures 3 & 4). The biggest of them reached 5 cm long (Figure 4). The fact that clayey sediments in the 1-4 m depth interval appeared severely damaged suggested that more than few nodules of gas hydrates were present in situ. Those that could not be observed on-board were probably smaller and dissociated faster during core recovery. Analysis of the first two sections of core GAS-CS14 did not reveal a similar degree of damage, suggesting that gas hydrates did not occur in the uppermost meter of sediment. There are however evidences for the presence of carbonate concretions within the first 5 cm of core GAS-CS14 (Figure 3). Those were taken as evidences for previous gas circulation up to the sea surface at this site.

In order to emphasize how the presence of gas hydrates affects the geo-mechanical properties of sediment, comparisons will be made with the piezocone data obtained at a reference site (GAS-CPTu05-S07 in Figure 2) located in a flat area, about 1.5 km away from site GAS-CPTu-07-S04. In table 2 presenting the characteristics of piezocone soundings, it appears that GAS-CPTu-07-S04 halted prematurely at 6.88 m depth below seabed, well before the maximum penetration of 30 m afforded by the Penfeld penetrometer. The halt in penetration was due to an alarm indicating that pore pressures exceeded the sensor measurement range.

Reference name	Piezocone	Date	Lat° N	Long° E	Water depth [m]	Penetration [m]	Cause of the refusal
GAS-CPTu05-S07	E3P3	21/09/15	43.931402	30.835220	876	30.00	-
GAS-CPTu07-S04	E3P3	25/09/15	43.939347	30.850726	729	6.88	Excess pressure

Table 2 : Summary of the characteristics of the piezocone soundings analysed in this report.

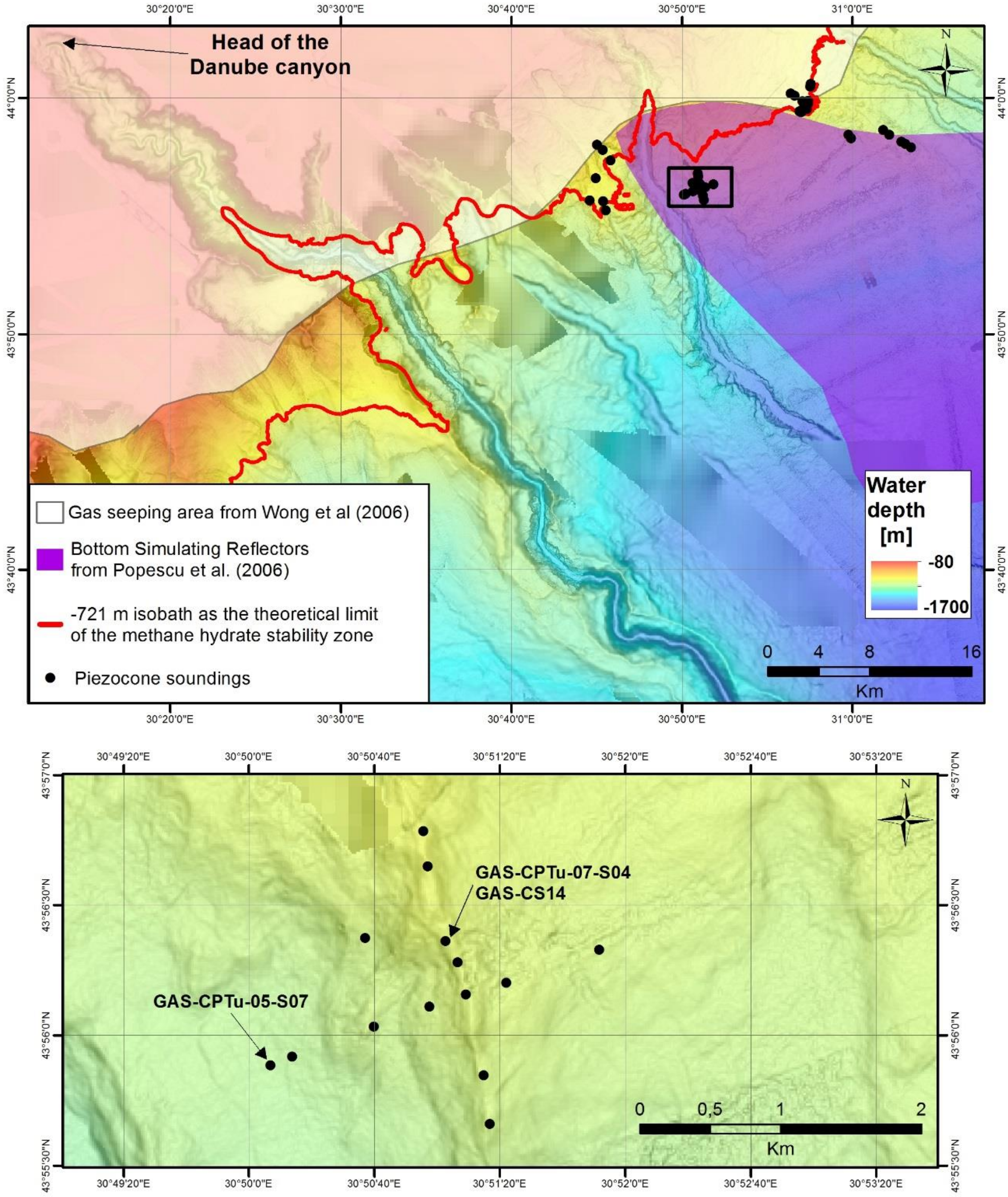

Figure 2: Top: Bathymetry map of the Romanian sector of the Black Sea showing the location of piezocone soundings carried out during the GHASS cruise (September 2015). The -721 m isobath (in red) indicates the theoretical landward limit of the methane hydrate stability zone. Bottom: Close-up showing the piezocone sounding at reference site GAS-CPTu-05-S07 and the GAS-CPTu-05-S07 sounding carried out where gas hydrates were recovered in core GAS-CS14.

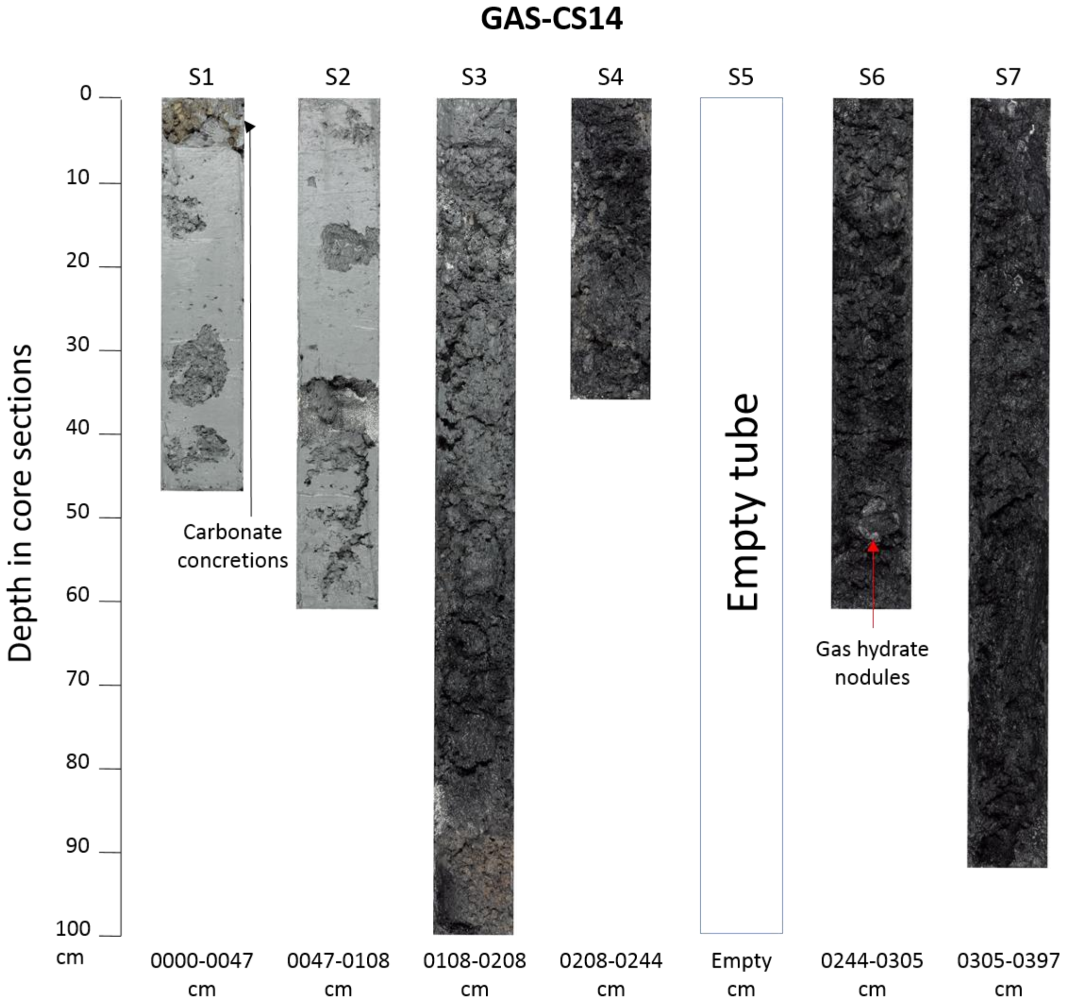

Figure 3: Pictures of the 7 sections of core GAS-CS14.

Figure 4: Close-up showing a gas hydrate nodule surrounded by severely damaged clays in core GAS-CS14.

2.3 Comparison of piezocone results

Figure 5 compares the piezocone profiles obtained where gas hydrates were recovered (GAS-CPTu07-S04) and at the reference site (GAS-CPTu05-S07). It reveals that, from the seabed down to 1 m depth, the profiles of the two soundings tend to follow the same trend, thus suggesting that sediment is of similar nature at both sites. On the q_t and f_s profiles of GAS-CPTu07-S04, this trend is punctuated by spikes at 10 cm depth which correlate with the presence of carbonate concretions observed in core GAS-CS14 (Figure 3).

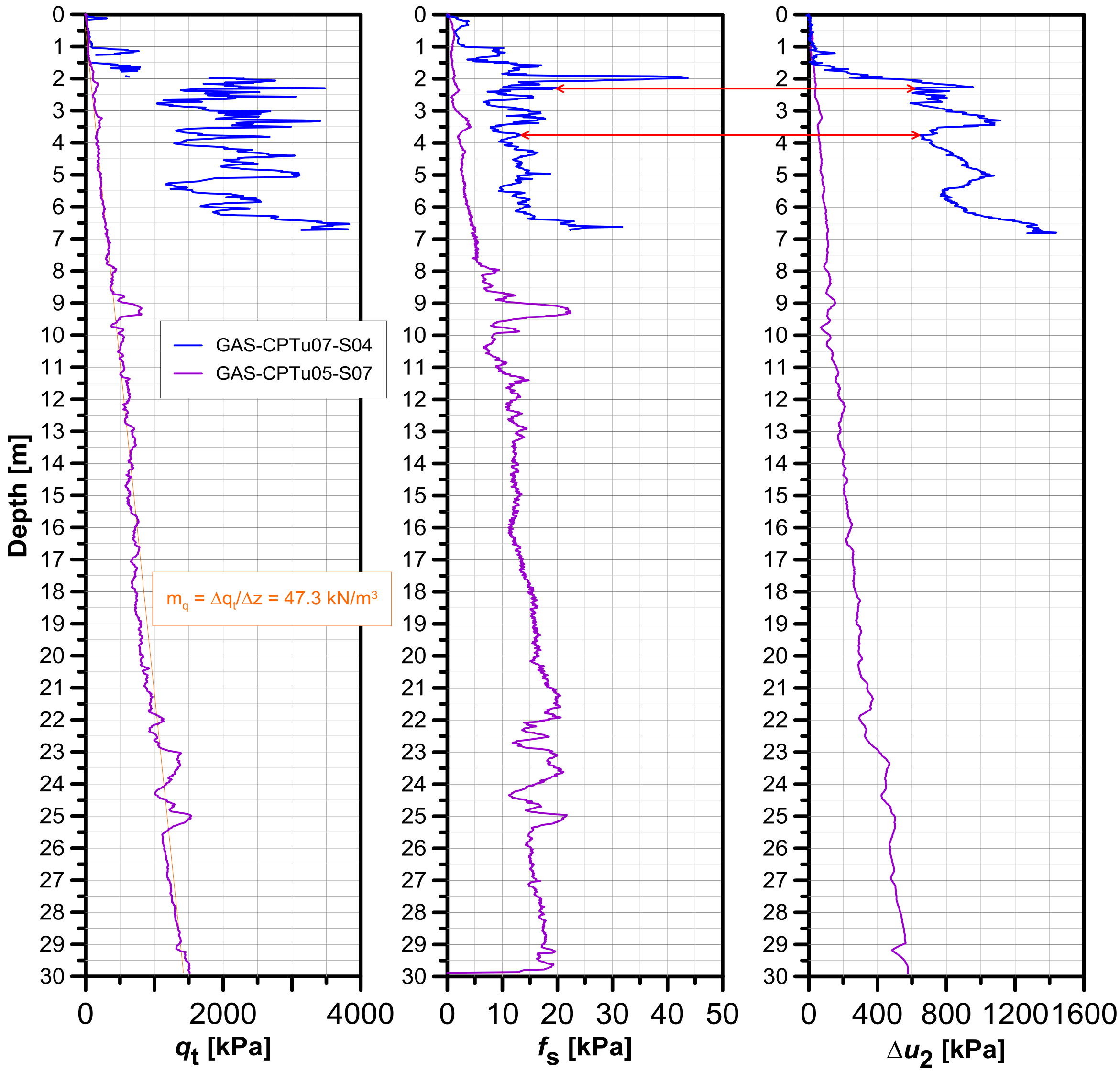

Figure 5: Depth profiles of corrected tip resistance, q_t, sleeve friction, f_s and excess pore pressure Δu_2 from soundings GAS-CPTu05-S07 and GAS-CPTu07-S04. The red arrows indicate where inclusions are suspected to have been pushed aside during penetration as explained in the text.

Below the uppermost meter, values of corrected tip resistance, q_t, sleeve friction, f_s, and pore pressure, Δu_2 are significantly higher for GAS-CPTu07-S04 compared to GAS-CPTu05-S07. The abrupt increases observed on all GAS-CPTu07-S04 readings from 1 m depth correlates well with inferences for the presence of gas hydrates from the same depth in core GAS-CS14 (Figures 3 & 5). Although GAS-CPTu07-

S04 readings strongly oscillate, comparison with those of GAS-CPTu05-S07 points out that the presence of gas hydrates is, on average, associated with a 10 fold increase in q_t and Δu_2 for a 5 fold increase in f_s. Oscillations in q_t and f_s are in phase on the GAS-CPTu07-S04 profiles. Those of Δu_2 are of lower frequency. These observations provide key information regarding the reliability of measurements in the presence of inclusions such as the gas hydrate nodules identified on core GAS-CS14. Ramsey (2010) has indeed emphasized that hard inclusions can be forced aside during penetration, thus creating local suctions impairing the performance of the pore pressure sensor. He noted that this process implying a local increase in lateral stress commonly manifests by sharp drops in pore pressure and complementary spikes in f_s. Based on the analysis of figure 5 such a process has perhaps happened twice during penetration without severely affecting the readings given the pore water pressure has never reduced drastically to the ambient pressure.

In order to further comparisons and highlight aspects of sediment behaviour during in situ testing, piezocone data had to be normalized before being used in a classification chart. Following the approach recommended by Schneider et al., (2008), normalised tip resistances: Q_t = $(q_t\text{-}\sigma_{v0})/\sigma'_{v0}$ and normalised excess pressures $\Delta u_2/\sigma'_{v0}$ were thus calculated from estimates of the total vertical stress, σ_{v0}, and of the vertical effective stress σ'_{v0}. Vertical stresses were estimated from values of total unit weight, γ_t, derived from the corrected tip resistance-depth ratio (m_q = $\Delta q_t/\Delta z$) following the method reported by Mayne (2014). This approach was only applied to piezocone readings at reference site GAS-CPTu05-S07 given statistical analyses of a database in gas hydrate-bearing sediments have not been achieved yet.

The m_q ratio was found equal to 47.3 kN/m^3 for the q_t profile of GAS-CPTu05-S07 (Figure 5). A profile of total vertical stress, σ_{v0}, was obtained by integrating values of total unit weight calculated using the following equation suggested by Mayne (2014):

$$\gamma_t = 0.636(q_t)^{0.072}(10 + \frac{m_q}{8})$$

From the resulting profile (Figure 6), a profile of vertical effective stress, (σ_{v0} = $\sigma'_{v0}\text{-}u$) was derived assuming hydrostatic pore pressure conditions (u = γ_w . z with γ_w = unit weight of water).

The same profiles of total and effective stress were used to normalise the tip resistance and pore pressure data from both soundings GAS-CPTu05-S07 and GAS-CPTu05-S07. Since the unit weight of gas hydrates (9.2 kN/m^3) is lower than that of seawater (10.3 kN/m^3), normalised parameters Q_t and $\Delta u_2/\sigma'_{v0}$ are underestimated in gas hydrate-bearing sediments. The extent of the underestimation is unknown as it depends on gas hydrate concentration.

Figure 7 shows the normalised piezocone parameters in the soil behaviour classification charts developed by Schneider et al., (2008). Data from GAS-CPTu07-S04 where gas hydrates were recovered clearly distinguish from those of GAS-CPTu05-S07 by showing Q_t and $\Delta u_2/\sigma'_{v0}$ values close to the upper limits of the chart. It is noteworthy that the majority of the data from GAS-CPTu07-S04 plots in zone 1b indicating a clay behaviour similarly with the data from GAS-CPTu05-S07. A significant portion of GAS-CPTu07-S04 data also plots in zone 1c suggesting that the presence of hydrates tend to increase strength sensitivity. None of the data from GAS-CPTu05-S07 plots in zones 2 and 3 which indicates that piezocone penetration occurred fully undrained in gas hydrate-bearing sediments at this site.

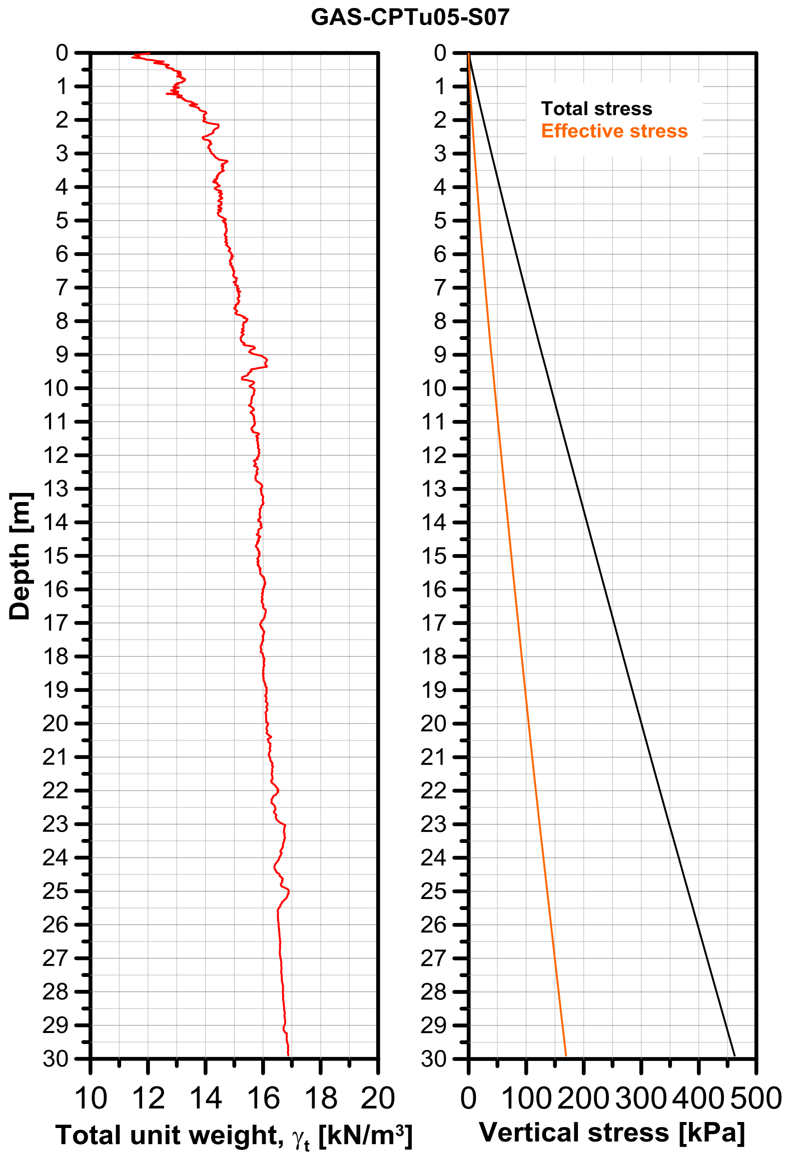

Figure 6: Depth profiles of total unit weight, total vertical stress and vertical effective stress from GAS-CPTu05-S07 data.

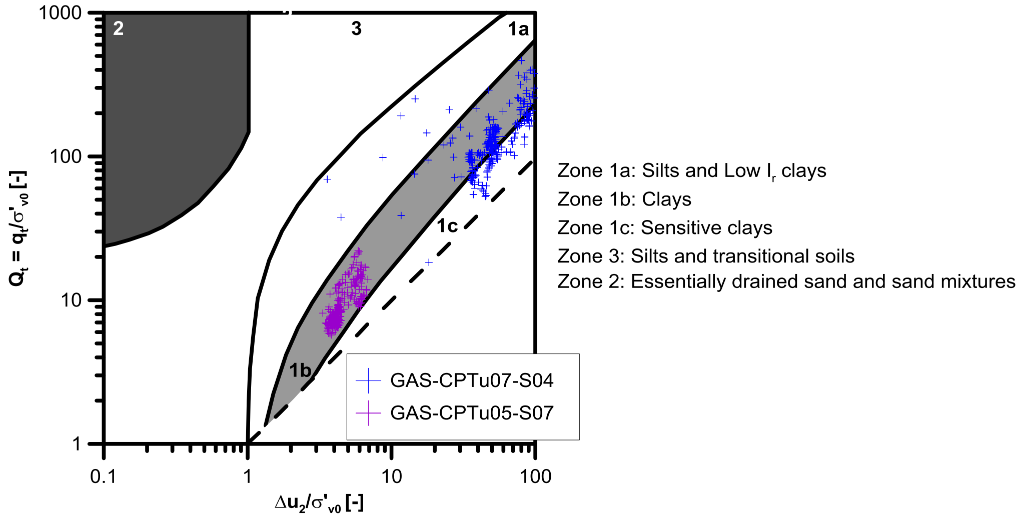

Figure 7: Piezocone data plotted in the Q_t-$\Delta u_2/\sigma'_{v0}$ classification chart from Schneider et al., (2008).

3 Derivation of geo-mechanical properties from piezocone results

Piezocone readings can be used either separately or together for deriving geo-mechanical properties through empirical correlations. Although an improved set of correlations has been developed over the last 20 years for a wide range of soils, their reliability and applicability vary according to precedent and local experience. The properties derived from piezocone sounding in gas hydrate-bearing sediments must thus be treated with caution due to the lack of statistical study on this soil type. Examination of the soil behaviour classification chart (Figure 7) suggests that, although 'unusual', gas hydrate-bearing sediments behave in the same way as stiff and sensitive clays. This motivated the application of existing empirical correlations developed to derive properties of undrained soils from both GAS-CPTu05-S07 and GAS-CPTu07-S04 soundings. Based on the syntheses by Robertson (2012) and Mayne (2014) it was estimated that effective yield stress, constrained modulus, peak undrained shear strength and strength sensitivity are the properties that can be reliably derived from sounding GAS-CPTu05-S07 at the reference site where usual clay sediments have been encountered. Derivation of similar properties in gas hydrate-bearing sediments can currently only be considered as approximate at best.

3.1 Estimation of the effective yield stress

3.1.1 Method

Mayne et al., (2014) reported a unified approach to the evaluation of effective yield stress, σ'_{vy}, using the following power law expression:

$$\sigma'_{vy} = 0.33(q_t - \sigma_{v0})^{m\prime}(\frac{\sigma_{atm}}{100})^{1-m\prime}$$

Where σ_{atm} is the atmospheric pressure (100 kPa) and the exponent m' a parameter decreasing with mean grain size. According to Mayne et al., (2014), m' can be directly assessed through the following equation:

$$m' = 1 - \frac{0.28}{1 + (\frac{I_c}{2.65})^{25}}$$

where I_c is a material index found from (Robertson 2009):

$$I_c = \sqrt{(3.47 - logQ_t)^2 + (1.22 + logF_r)^2}$$

with the normalised tip resistance: Q_t = $(q_t\text{-}\sigma_{v0})/\sigma'_{v0}$ and, the normalized friction ratio F_r= $[f_s/(q_t\text{-}\sigma_{v0})]100\%$.

3.1.2 Results

Figure 8 shows the I_c and σ'_{vy} profiles derived from soundings GAS-CPTu05-S07 and GAS-CPTu07-S04. Following the approach developed by Robertson (2009), the material index I_c can be used for classifying soil type. The classification relying on I_c agrees with that presented in Figure 7 for GAS-CPTu05-S07 by highlighting an undrained clay behaviour. There is however a striking discrepancy between the two classifications for GAS-CPTu07-S04 since values of I_c suggest a drained response of gas hydrate-bearing sediments while the classification chart by Schneider et al., (2008) pointed out a fully undrained response. This is attributed to the 'unusual' nature of gas hydrate bearing sediments and their low friction ratio compared to typical clays, since the classification based on normalised excess pore pressure is undoubtedly best suited to determine whether penetration occurred under drained or undrained conditions. Although this warrants caution when interpreting geo-mechanical properties obtained with I_c in the presence of gas hydrates, comparison of the profiles of effective yield stress, σ'_{vy}, obtained for GAS-CPTu05-S07 and GAS-CPTu07-S04 is coherent. That is, while σ'_{vy} of sediments at the reference site tends to increase linearly with depth, that of gas hydrate-bearing sediments oscillates around a mean value of about 84 kPa without a clear trend with depth. Such a feature is taken as reflecting the decreasing relevance of effective stress as hydrate saturation increases, as pointed out by Waite et al., (2009). Profiles of yield stress ratio (YSR = σ'_{vy} / σ'_{v0}) are presented in figure 8 to support this view.

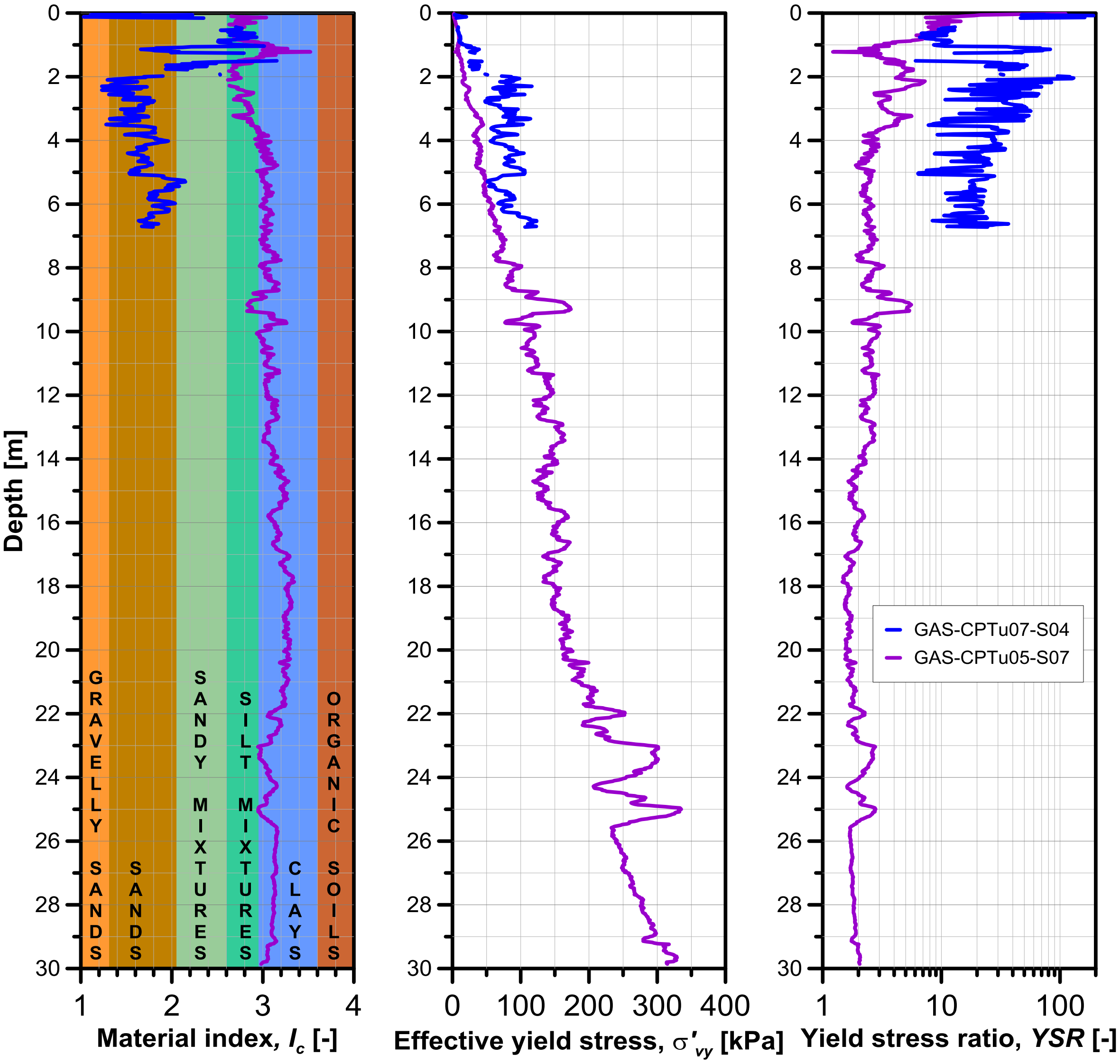

Figure 8: Depth profiles of material index, I_c, effective yield stress, σ'$_{vy}$, and yield stress ratio, YSR, of soundings GAS-CPTu05-S07 and GAS-CPTu07-s04.

3.2 Estimation of the constrained modulus

3.2.1 Method

Existing correlations between constrained modulus, M, and piezocone results typically have the form:

$$M = \alpha_M(q_t - \sigma_{v0})$$

According to Robertson (2012) the factor α_M can be determined from the index material I_c and from the stress-normalised tip resistance Q_{tn}:

$$Q_{tn} = \left[\frac{(q_t - \sigma_{v0})}{\sigma_{atm}}\right]\left(\frac{\sigma_{atm}}{\sigma'_{v0}}\right)^n$$

Where n is a stress exponent related to the index material I_c through the following equation:

$$n = 0.381(I_c) + 0.05\left(\frac{\sigma_{atm}}{\sigma'_{v0}}\right) - 0.15$$

Robertson (2012) suggested that:

- When I_c > 2.2 and Q_{tn} <14 then α_M = Q_{tn}
- When I_c > 2.2 and Q_{tn} >14 then α_M = 14
- When I_c < 2.2 then $\alpha_M = 0.03\left[10^{(0.55I_c+1.68)}\right]$

3.2.2 Results

Figure 9 shows the profiles of I_c, stress-normalised tip resistance Q_{tn} and, constrained modulus M, derived from soundings GAS-CPTu05-S07 and GAS-CPTu07-S04. Comparison of these plots reveals that for GAS-CPTu-05-S07, the values of I_c are constantly above 2.2 while, except for the upper 50 cm, Q_{tn} is smaller than 14. The factor α_M was thus taken equal to Q_{tn} to derive M values below 50 cm depth. From the general trend of the resulting profile it appears that compressibility decreases with depth inversely as M. Besides, given the low values of I_c and high values of Q_{tn} obtained for GAS-CPTu-05-S07, M values in gas hydrates-bearing sediments were most commonly calculated with α_M factors derived from I_c. Analysis of the resulting profile reveals that in gas hydrate-bearing sediments M is 20 to 40 times higher than at the reference site. This indicates that the compressibility is significantly reduced in the presence of hydrates in agreement with the results presented by Sultan et al., (2010).

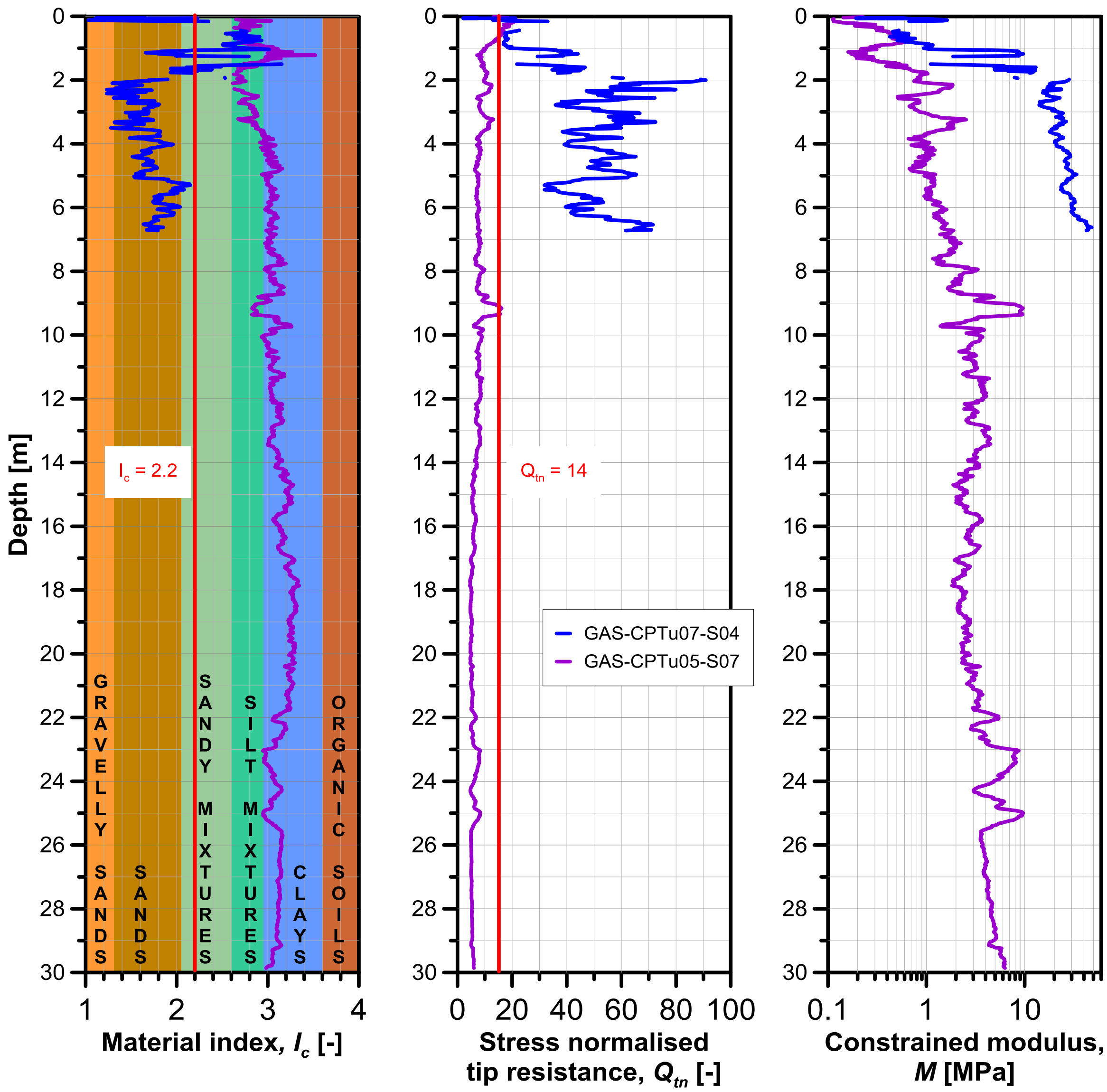

Figure 9: Depth profiles of material index, I_c, stress-normalised tip resistance, Q_{tn}, and constrained modulus, M, of soundings GAS-CPTu05-S07 and GAS-CPTu07-s04.

3.3 Estimation of the peak undrained shear strength

3.3.1 Method

Several theoretical studies support the use of a relationship between piezocone results and the peak undrained shear strength, Su_p of the form:

$$Su_p = \frac{(q_t - \sigma_{v0})}{N_{kt}}$$

Where N_{kt} is a cone factor depending on soil stiffness, stress history (or yield stress ratio) and strength sensitivity; the later of these parameters having the largest influence (Robertson 2012). In addition to these soil parameters, N_{kt} depends upon the mode of testing used for calibration in the laboratory. Its value typically varies from about 10 to 20. Low et al. (2010) found the value of N_{kt} = 13.6 ±1.9 to be appropriate for many situations in soft clays. According to the classification chart presented in figure 7 this value can be reliably used to estimate Su_p from piezocone results at the reference site GAS-CPTu-05-S07. Given the trend in response of the gas hydrate-bearing sediments in this chart and the lack of experience with this 'unusual' soil type, it is judged appropriate to use N_{kt} values of 10 and 20 to estimate a range of possible peak undrained shear strengths.

3.3.2 Results

Values of peak undrained shear strength, Su_p, obtained with N_{kt} factors of 10 and 20 for GAS-CPTu-07-S04 are compared to that obtained for GAS-CPTu-05-S07 with N_{kt} = 13.6 in figure 10. The Su_p profile at the reference site generally follows a linear trend. The slope of the trend line allows to estimate an undrained shear strength ratio, Su_p / σ'_{v0}, of 0.4. By contrast, the values of Su_p in gas hydrate-bearing sediments do not show a tendency to increase with depth. They are oscillating with a peak-to-peak amplitude exacerbated by the use of a N_{kt} factor of 10. The maximum Su_p obtained with this factor reaches 375 kPa at 6.8 m below seabed while the maximum Su_p value at the reference site is on the order of 80 kPa at 30 m below seabed. Comparison between values at similar depth reveals that the presence of gas hydrate is overall associated with a 5 to 14 fold increase in Su_p with N_{kt} = 20 or a 10 to 28 fold increase in Su_p with N_{kt} = 10.

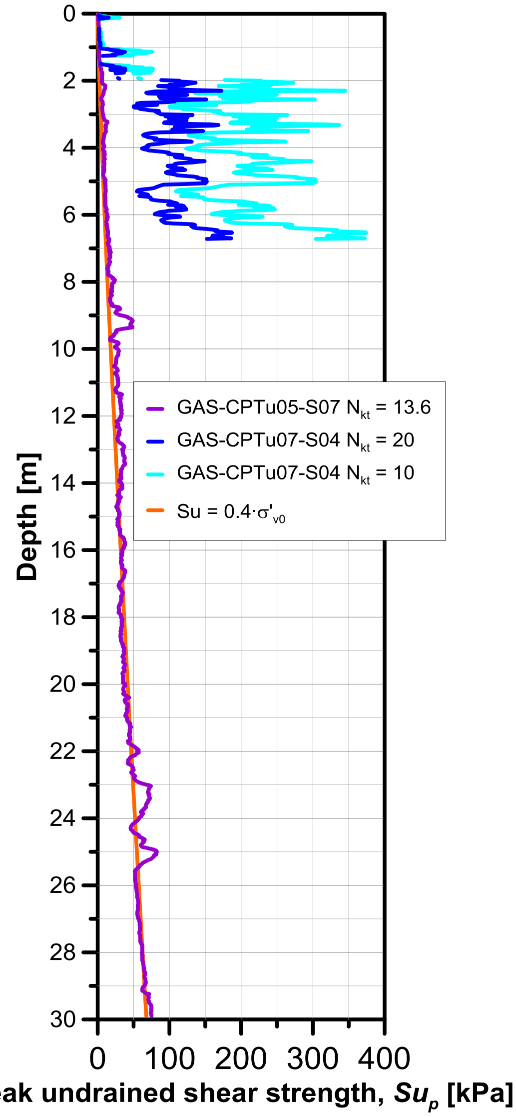

Figure 10: Depth profiles of peak undrained shear strength, Su_p, of soundings GAS-CPTu05-S07 and GAS-CPTu07-s04.

3.4 Estimation of the strength sensitivity

3.4.1 Method

With piezocone sounding, the sleeve friction reading, f_s, is commonly assumed to be directly indicative of the remoulded undrained shear strength Su_r (Robertson 2009). As a result, the strength sensitivity, S_t, of clay can be estimated by calculating the ratio of peak shear strength to f_s:

$$S_t = \frac{Su_p}{Su_r} = \frac{(q_t - \sigma_{v0})}{N_{kt}}\left(\frac{1}{f_s}\right)$$

In line with the arguments presented in the previous chapter, values of S_t were calculated using a N_{kt} factor of 13.6 for the reference site (GAS-CPTu-05-S07) and with two N_{kt} factors of 10 and 20 for gas hydrate-bearing sediments (GAS-CPTu-07-S04).

3.4.2 Results

Analysis of figure 11 reveals that the strength sensitivity, S_t, of sediments at the reference site (GAS-CPTu-05-S07) varies in the range 2 to 6. Sensitivities are overall 2.5 to 5 times higher in gas hydrate-bearing sediments depending on which value of N_{kt} is used to estimate Su_p. A maximum value of 37 is observed at 3.5 m on the curve derived with N_{kt} = 10.

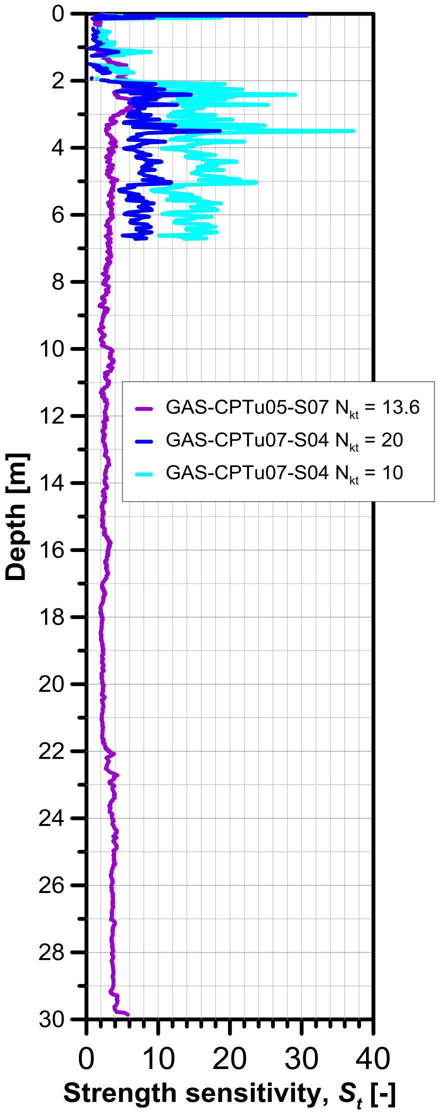

Figure 11: Depth profiles of strength sensitivity, S_t, of soundings GAS-CPTu05-S07 and GAS-CPTu07-s04.

4 Conclusion

This report has presented the results of two piezocone soundings carried out in the Romanian sector of the Black Sea during the GHASS cruise (September 2015). One of them was selected as core sampling at the same site provided ground truth for the presence of gas hydrates in clay sediments. The other sounding was selected to serve as a reference for comparing geo-mechanical properties of sediments with and without gas hydrates.

Two distinct classifications were used to identify the behaviour type of sediments during piezocone penetration. Each of them pointed out that, at the reference site, penetration occurred fully undrained as in typical clay soils. Besides, the 'unusual' characteristics of gas hydrate-bearing sediments was highlighted by the discrepancy between the two classifications. The discrepancy has been ascribed to the fact that gas hydrate-bearing sediments behave undrained as stiff or sensitive clays while they have lower friction ratio. Accordingly, similar empirical correlations were applied to estimate some geo-mechanical properties of reference and gas hydrate-bearing sediments. This allowed to point out that the presence of gas hydrates tends to increase the effective yield stress, peak undrained shear strength and strength sensitivity of sediments while it tends to decrease their compressibility. Although the extents to which gas hydrates affect these properties could have been estimated, the lack of experience and statistical correlation studies with gas hydrate-bearing sediments warrants caution in their use.

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