Gassy soils of the Llobregat delta: Impact on geomechanical characterization

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ABSTRACT

The presence of biogenic gas in the soft soils of the Delta del Llobregat at the Port of Barcelona has already been reported by various authors based on geophysical investigations and in-situ tests. As the impact of gas presence on soil behaviour remains uncertain, it is of interest to describe the behaviour of these gassy soils as they may affect future expansions of the Port of Barcelona.

Recently, in new geotechnical investigations at the Port of Barcelona, gas emissions have been observed, in several locations in the vicinity of the South breakwater, while performing in situ tests (CPTu and SDMT) or during borehole drilling. Samples were extracted from those boreholes that were subsequently used for laboratory tests.

Given the potential impact on geotechnical properties, the results of the investigation were utilized to increase the understanding of gassy soils. Essentially, the focus was on detecting anomalies in geotechnical parameters at the points where gas was detected. These anomalies were also correlated with observations of soil structure obtained from micro-CT scanning X-ray images of undisturbed samples from the zones where gas was present.

Keywords: gassy soils, soil cores, in-situ tests, geomechanical anomalies.

1. Introduction

Gassy soils are soils that contain gas bubbles, usually methane, in their pores. Biogenic methane is the most common type of gas found in gassy soils, and it is produced by microbial activity in anaerobic conditions (Fleischer et al., 2001; Sills & Thomas, 2002). Gas can occur in the seabed in three ways: dissolved, undissolved in the form of gas-filled voids, or as clathrates (Sills & Wheeler, 1992).

The behaviour and engineering properties of marine sediments hosting them may be significantly affected by free gas-filled voids, exsolution of dissolved gas and/or gas releases due to gas hydrates dissociation (Sultan et al 2012). It is known that gas can affect the mechanical behaviour and stability of the soils, especially under unloading (Hardy & Hemstock, 1963).

Gassy soils are a challenging and interesting topic in geotechnical engineering, as they involve multiphase, multiscale, and multi-physical phenomena. Understanding the effects of biogenic methane on the geotechnical properties of gassy soils can help to improve the design, construction, and management of offshore and coastal infrastructure, as well as to exploit the potential benefits and mitigate the possible risks of gassy soils. A number of accidents induced by the existence of gassy soils have been documented (Sobkowicz & Morgenstern, 1984; Rad et al., 1994; Rowe et al., 2002; Kortekaas and Peuchen, 2008; Sultan et al., 2012; Xu et al., 2017; Rowe & Mabrouk, 2018; Jommi et al., 2019).

Gas releases were spotted on the sea surface decades ago during offshore geophysical studies of the Llobregat prodelta. Due to the expansion of the port on the prodelta materials, studies were launched to locate the gas and assess its potential impact on new projects.

2. Evidence of gas presence in Prodelta Llobregat sediments

Apart from the gas releases detected on the sea surface, two additional studies evidenced the presence of gas. These findings indicate the potential impact on the geomechanical properties and, as a consequence, on the geotechnical stability of the port's structure.

2.1. Curtain reflection area

The Barcelona Port Authority carried out a geophysical study in the expansion zone. This study revealed a curtain reflection (or acoustic shadow) area due to gas that affected the main part of the breakwater and the Prat quay alignment, (Alonso et al. 1995). These results had an impact on the expansion design because the main part of the curtain reflection area is inside the inner harbour. However, it was not until later, when anomalies in the soil behaviour were detected, that more resources were allocated to investigate what was going on.

2.2. Anomalous soil behaviour

Firstly, the piezometer records in the shadow zone gave unusual results reported in Tarrago & Gens (2018): (i) sudden changes of excess pore pressure and (ii) phase difference between closed and opened piezometers and attenuation of pore water pressure caused by tides, as described by Wheeler (1988), Okusa (1985) and Brandes (1999) in gassy soils.

Secondly, a comprehensive site investigation was carried out in 2007 in the area where the BEST container terminal is currently placed. 18 boreholes or CPTu failed during sounding because of gas presence.

Soil specimens drilled and recovered from boreholes were mainly silty-clay with sand layers. Methane (CH_4) was found in eleven samples according to BAT permeameter test results. Only two samples had a gas saturation of 100%, showing the presence of free gas. The rest had gas saturation in the range of 1% and 72%.

Two CPTu soundings, where free methane was found, match with reported behaviour by Sultan et al. (2007), Sultan et al. (2010) and Steiner et al. (2013).. It has been found that the ratio of undrained shear strength over effective vertical stress (c_u/σ'_v) may be an indicator for the presence of gas, as values lower than 0.25, which is the usual value for this soil, were found in several piezocones. This drop may be due to gas moving upwards (Tarrago & Gens 2018; Sultan et al. 2007).

3. Emplacement of a new quay and the geotechnical site investigation

The expansion of the Port of Barcelona is ongoing and the new Catalunya quay, sheltered by the South breakwater, is planned.

The construction of this quay will possibly involve serval stages. Firstly, the dredging of a trench to build a bench is needed. The bench will serve as the foundation for the quay wall. The quay wall will be composed of concrete caissons. After closing the quay wall, the enclosure will be filled with soil above sea level. The resulting esplanade covers an area of more than 30,000 m^2 where container operations are planned.

Therefore, the construction of the quay will involve two stress changes:

i. Local vertical unloading of the natural ground during the excavation for the bench. With this, a dredging height of 10 m could be reached resulting in a reduction of the vertical stress ($\Delta\sigma_v$) of the order of 185 kPa. Thus, according to Sultan et al. (2012), the unloading process of fine-grained gassy soils will reduce dramatically the effective vertical stresses, higher compressibility will be reached and the shear strength will reduce due to the exsolution of gas.
ii. Vertical load growing during the construction will increase in the area of the esplanade until reaching $\Delta\sigma_v > 400$ kPa.

Both stress changes can generate significant changes in the gas condition present in the gassy soil that must be evaluated. When gassy soil is vertically loaded, this can cause a rise in the gas pressure and a decrease in the soil permeability. The gas can migrate to areas of lower pressure or escape to the atmosphere, which can affect soil stability and strength (Sills & Thomas, 2018).

It is challenging to evaluate the behaviour of gas-bearing soils, especially based on laboratory tests of undisturbed samples and in-situ tests. For this reason, it was initially decided to carry out a general geotechnical campaign with in-situ tests that could already provide information on the presence of gas in the soil or the quality of the soil:

- Laboratory tests on samples extracted with piston: degree of saturation, organic matter content, void ratio. Unfortunately, those tests are still in post-processing.
- Scanning X-ray images from soil cores.
- In-situ: undrained shear strength from CPTu and SDMT, pore water pressures from CPTu, V_S from SDMT.

As the authors were especially interested in determining the in-situ degree of saturation, tests with the sonic cone developed by Ifremer (Sultan et al., 2007) were intended to be carried out to characterize in-situ the velocity of P waves (V_P). However, this was not possible.

Thus, for the construction of the quay, 265 in-situ tests (CPTu and SDMT) and 189 boreholes with laboratory tests on recovered soil samples have been performed (see Fig. 1).

Figure 1. Geotechnical site investigation of the future Catalunya quay, 2022-2023. Points: red (boreholes), blue (CPTu) and green (SDMT).

4. Recorded gas releases

Gas release (or discharge) during the execution of the site investigation was observed in 75 of the investigated locations. Based on the collected data, the presence of gas has been localised according to the duration of the gas release, as shown in Fig. 2.

It was detected that the gas releases were different depending on whether they occurred in CPTu and SDMT soundings or in drilling boreholes. In the soundings, the gas release was detected during the test or when removing the CPTu and SDMT probes from the ground. No interruptions during testing were reported. In these cases, the duration of gas release after the sounding was measured. In points where the gas release time was not determined have been marked on the map with yellow dots. On the other hand, in the boreholes, the time of gas release was measured during the drilling process as drilling operations had to be stopped for safety reasons when gas was encountered. The time varies between 1 minute and 3000 minutes (≈48 hours). Generally, a longer duration of the gas discharges was detected in the south area of the site (Fig. 2).

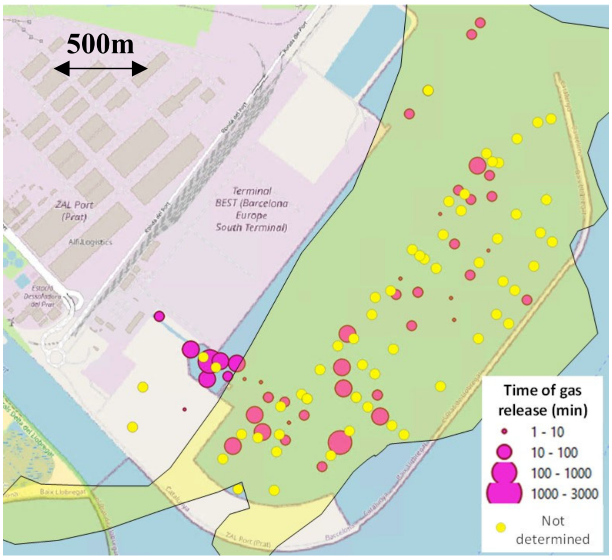

Figure 2. Plan view of the points with gas discharge according to its length, and curtain reflection area (yellow shaded area).

Gas discharges were detected in the soundings throughout the entire site investigation area. On the contrary, the gas discharges in borehole drilling were more localized despite having a similar grid of boreholes in the entire study area.

The gas releases in the boreholes occurred after drilling an average of 37 m deep, with depth values between 18 and 63 m. Gas releases were greater in the boreholes than in the soundings (CPTu and SDMT). This is mainly explained based on the adopted methodology as the casing drilling creates a drain at the bottom of the borehole. Another fact that may have influenced these differences is that all the soundings did not reach depths greater than 40 m while all the boreholes reached 60 m at least.

There is a certain relationship between gas release and neighbouring points according to the drilling or sounding date. This indicates the presence of continuous layers or at the same depths. Nevertheless, it also exists isolated gas realeases that indicate that soil layers with gas presence inside would be distributed erratically in the stratigraphy of the sediments.

The affected area agrees with the shielding area detected by Alonso et al. (1995) except in the area of the south east of the BEST Terminal. In this last area, there were up to 7 leaks, with one of them emanating gas for up to 48h.

5. Scanning X-ray images from soil cores

Although no cores could be recovered in the boreholes with high gas presence, piston samples were extracted in soils with lower gas presence. Scanning X-ray images of several samples were carried out.

The investigation points 005 and 208 where gas presence was identified are examined in more detail: These locations were triple points composed of borehole, CPTu and SDMT. Gas was released in the CPTu 005. Nevertheless, one day later during the drilling of the borehole, no gas was released. In contrast, no gas was released in the CPTu 208 while one day later, during the borehole drilling, gas was released at 39 m depth.

Three samples from 005 were scanned, as shown in Fig. 3. The soil description according to the borehole log is silty clay. Two samples from 208 were also scanned (Fig. 4). In this case, more permeable soils were described in the borehole log: fine sand in 208a sand silt in 208b.

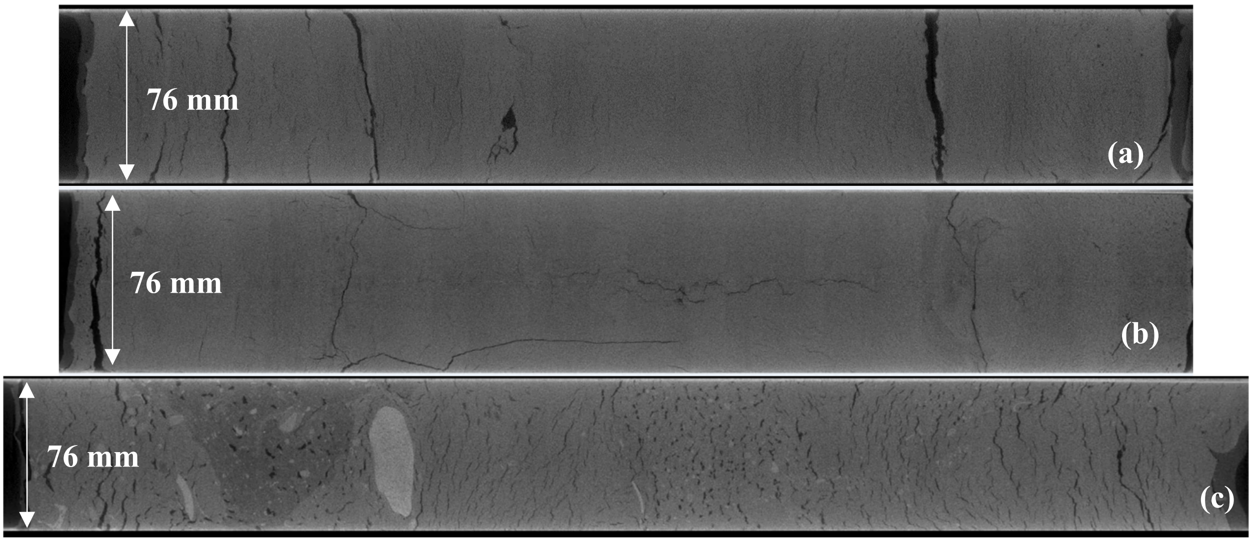

Figure 3. Scanning X-ray images from 005, (a) at 30m depth, (b) at 40m and (c) at 50 m depth.

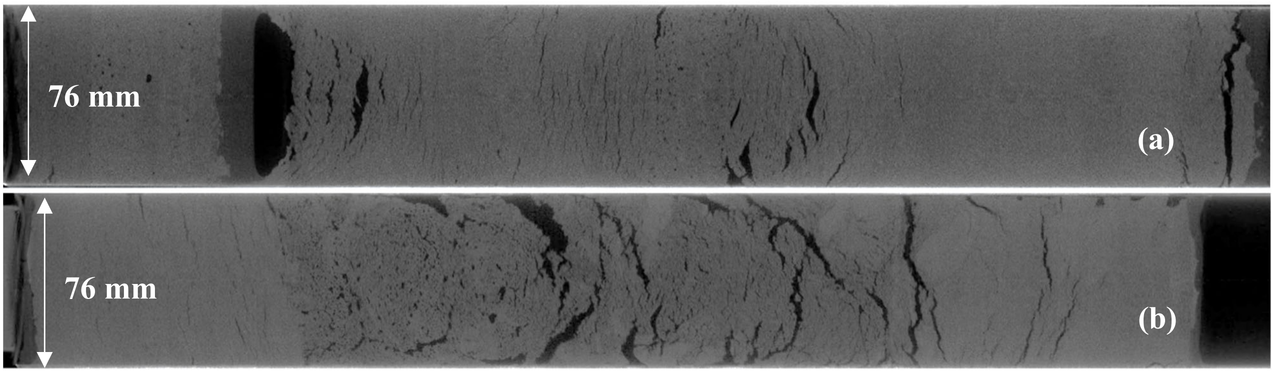

Figure 4. Scanning X-ray images from 208, (a) at 36m depth and (b) at 43m depth.

Although some fractures and dragging have been detected in scanning X-ray images, probably generated during sample recovery, the distinguished texture, porosity (Ø 1-5 mm) and rounded shapes observed in the samples 005c, 208a and 208b are very similar to the features described by Wheeler et al. (1988). Likewise, it should be taken into account that the porosity or damage observed may be caused by exsolution and expansion of the gas when removing the soil sample (Sultan et al. 2012). These textures are then suitable for the presence or circulation of gas through the soil.

6. In-situ test results related to gas presence

In-situ tests performed in the same location as the boreholes 005 and 208 and,thus, affected by gas release are evaluated. Despite the detected textures, no remarkable anomalies have been identified in terms of the primary parameters of CPTu (q_c, f_s or u_2) and SDMT (K_D and V_s).

According to the observed texture, where abundant porosity is appreciated, one could expect that the soil resistance would be lower, as Sultan et al. (2007) and Tarragó & Gens (2018) detected. Thus, the undrained shear strength (c_u) was evaluated from CPTu and DMT recordings with gas release in point 005 and point 208 (Fig. 5). The expressions used to calculate c_u with CPTu (Eq. 1) and DMT (Eq. 2) recordings are the following:

$$c_u = (q_c - \sigma_{v0})/N_{kt} \qquad (1)$$

where q_c is the cone resistance, σ_{v0} is the total vertical stress and N_{kt} is the cone factor. A value of 15 was adopted for N_{kt} in this study.

$$c_u = 0.22 \cdot \sigma'_{v0} \cdot (0.5 \cdot K_D)^{1.25} \qquad (2)$$

where σ_{v0} is the effective vertical stress and K_D is the in-situ horizontal stress ratio.

The lower limit of c_u values from CPTu is close to $0.25 \cdot \sigma'_v$. In contrast, c_u from DMT is generally higher than $0.30 \cdot \sigma'_v$.

A gas release occurred at 39 m depth in point 208, but no significant reduction in c_u/σ'_v (remaining close to 0.25) is evident. Therefore, the relationship between gas release and strength reduction is not valid in this case. However, to evaluate if this behaviour is recurrent, c_u/σ'_v is evaluated for the entire site (as shown in Fig. 6). The c_u/σ'_v profiles are separated into 3 zones:

A. outside the curtain reflection area (Alonso et al. 1995) without gas release.
B. within the curtain reflection area with gas release at the same location or at a point less than 10 m away.
C. within the curtain reflection area without gas release.

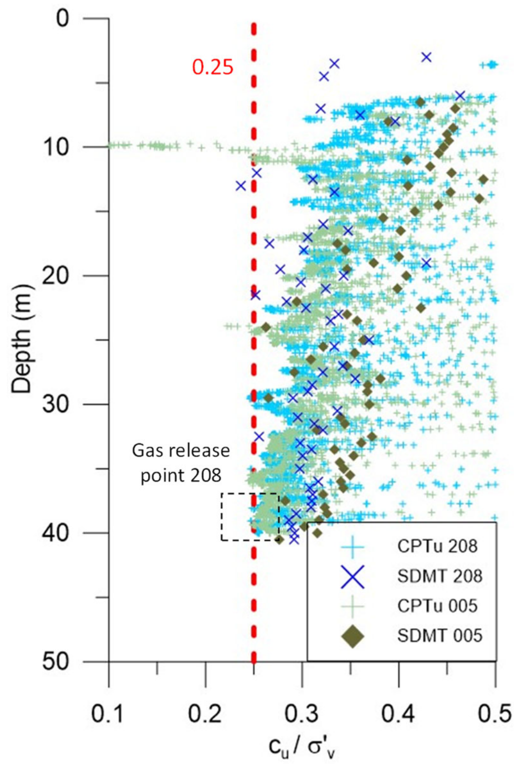

Figure 5. Undrained shear strength to effective vertical stress ratio profile from point 005 and point 208.

There are punctual reductions of c_u/σ'_v ratios below 0.20 in zones B and C. Despite being relatively close, such c_u/σ'_v reduction is not observed in zone A. Moreover, a general reduction of c_u/σ'_v ratios below 0.25 is detected in zones B and C. While in zone A, the reduction is less significant, and the usual values of $c_u=0.25 \cdot \sigma'_v$ for the silty-clay prodelta are reached.

These results suggest that the presence of gas could be affecting the undrained shear strength of the prodelta sediments. This effect is more pronounced in the curtain reflection area where soil strength has been systematically damaged by the presence of gas.

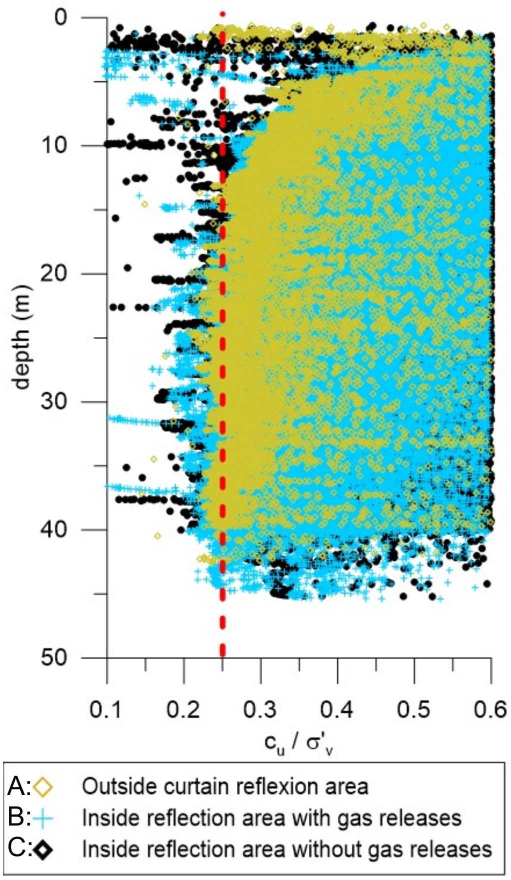

Figure 6. Undrained shear strength to effective vertical stress ratio profiles from CPTu of site investigation.

7. Discussion and conclusion

Gassy soils are commonly found in deltaic areas or regions where new sediments accumulate. These soils sometimes pose challenges in terms of their geomechanical characterization.

A curtain reflection area was detected by a geophysical seismic investigation (Alonso et al., 1995), indicating the presence of gas in the prodelta sediments of the Llobregat River.

Currently, an extensive geotechnical site investigation has been carried out in this area due to the Port of Barcelona's plan to construct the Catalunya quay. Interestingly, gas emissions have been observed throughout the area during this site investigation.

Scanning X-ray images results from the recovered cores, obtained from drilling with gas releases, reveal porosity (Ø from 1 to 5 mm) and soil damage. This texture is likely produced due to the effect of gas exsolution and expansion when removing the soil sample (Sultan et al., 2012).

The results of undrained shear strength obtained from CPTu and SDMT tests, which coincided with the cores extracted from gassy soil, did not exhibit any clear correlation. However, when evaluating all CPTu data from the campaign, a relationship between undrained shear strength and gas presence was identified. There is a systematic reduction in c_u (in-situ) < $0.25 \cdot \sigma'_v$ within the curtain reflection area, which slightly increases in the surrounding areas.

The undrained shear strength reduction can be linked to the presence of gas, as reported in Sultan et al. (2007) and Tarragó & Gens (2018).

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