Gas entrapment and migration in deltaic soils containing biogenic methane: challenges for site investigation and volume estimation

Dani Tarragó[1,2], *Enrique* Romero[2,1*], and *Antonio* Gens[2,1]

[1] Research Cluster Geomechanics and Hydrogeology, International Centre for Numerical Methods in Engineering, Barcelona, Spain
[2] Department of Civil and Environmental Engineering, Universitat Politècnica de Catalunya, Barcelona, Spain

1 Introduction

The presence of biogenic methane in soft deltaic sediments poses a major challenge for geotechnical characterisation, particularly in marine environments where access is limited and sampling inevitably disturbs the natural stress state. This issue is especially relevant in the Llobregat prodelta, where multiple field campaigns have documented persistent gas releases during drilling and penetration tests. These emissions, sometimes lasting more than 48 hours, indicate localised gas accumulations within specific sedimentary layers. However, despite extensive field evidence, no current in-situ technique can quantify gas content or pressure conditions without inducing significant perturbations. As a result, the behaviour of these partially saturated soils remains poorly understood, and the mechanisms governing gas entrapment, migration, and release require a more rigorous analytical framework.

Previous investigations in the area (e.g., [1, 2]) identified surface gas emissions and geotechnical anomalies consistent with subsurface gas pockets. These anomalies include reductions in undrained shear strength ratios, attenuated pore-pressure responses, and irregular dissipation curves during CPTu and SDMT testing. Although these indicators suggest the presence of gas, they do not permit quantification, nor do they distinguish between discontinuous gas bubbles and connected gas pathways. The heterogeneity of the sedimentary environment further complicates interpretation: gas occurrences do not consistently correlate with organic-matter content, nor do they follow predictable stratigraphic patterns. Instead, gas tends to accumulate within silty-sand or sandy-silt layers that act as temporary reservoirs, confined beneath low-permeability clayey silts.

Gassy sediments are a challenging topic in geotechnical engineering because they involve multiphase, multiscale, and multiphysical phenomena. Understanding the effects of biogenic methane on the geotechnical properties of gassy soils can help improve the design, construction, and management of offshore and coastal infrastructures and mitigate potential risks associated with gassy soils (e.g., [3, 4]).

This study develops a methodological framework to evaluate the unsaturated behaviour of these gas-bearing sediments and to estimate the initial gas volume released during drilling. The approach integrates capillary pressure-saturation curves, effective gas permeability assessment, and a generalised Darcy's law for compressible fluid.

The objective is twofold: (i) to determine the gas pressure required to initiate desaturation and enable gas breakthrough in the sediment matrix, and (ii) to estimate the volume of gas released during documented escape events, using field observations and soil-specific hydraulic properties.

2 Geological and geotechnical context

The Llobregat delta comprises a sequence of soft, fine-grained deltaic sediments interbedded with silty-sand layers. These coarser layers often contain organic matter capable of generating biogenic methane. Gas accumulations are typically found between depths of 70 m (the upper boundary of the deltaic lower aquifer) and 35 m, where drilling campaigns have repeatedly encountered gas releases. The thickness of gas-bearing layers ranges from 0.3 m to 1.0 m, consistent with the observed silty-sand layer. Figure 1 presents an X-ray computed tomography of a gas-bearing soil core at 43 m depth.

Field observations show that gas releases occur both in conventional boreholes and during the extraction phase of CPTu tests, indicating either continuous gassy layers at similar depths or gas pockets distributed throughout the sediment stratigraphy. In boreholes, stress reductions at the bottom of the casing alter hydraulic gradients and may allow gas to enter the casing if the gas pressure exceeds the internal water column pressure.

By contrast, in CPTu tests, gas rarely escapes during penetration but often migrates upwards during cone extraction, thereby releasing trapped gas from the pore spaces of seafloor sediments. The duration and intensity of gas emissions vary widely, and longer events tend to exhibit stronger bubbling and occasional sediment transport (for example, one leak emitted gas for 48 hours). It has been found that the ratio of undrained shear strength to effective vertical stress may indicate the presence of gas, with values below 0.25 observed in several piezocones [2].

Stress changes can significantly alter gas conditions in gassy soils, and these changes must be evaluated. When compressible gassy soils are vertically loaded, gas pressure can increase, and gas effective permeability decreases. In this context, the gas can migrate to areas of lower pore pressure or escape to the atmosphere, thereby inducing changes in soil volume. These observations highlight the need to understand the unsaturated behaviour of the soil-gas-water system,

* Corresponding author: enrique.romero-morales@upc.edu

particularly the capillary pressure (matric suction) that controls gas entry and breakthrough, and the effective permeability conditions that govern gas transport.

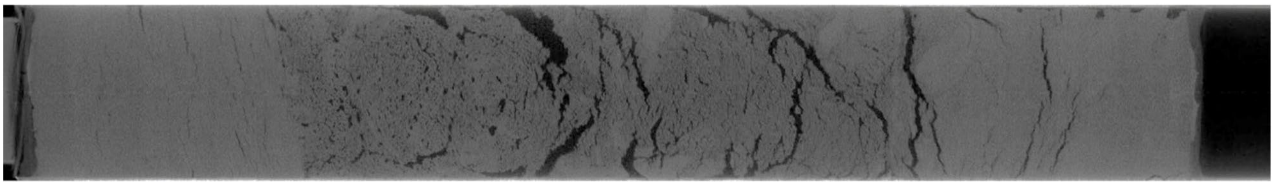

Figure 1. X-ray computed tomography of a gas-bearing soil specimen at 43 m depth. Core diameter:76 mm (adapted from [2]).

3 Unsaturated behaviour: capillary pressure and gas breakthrough

Gas invasion and accumulation in saturated sediment require the gas pressure u_g to exceed the pore-water pressure u_w by more than the capillary gas entry pressure ($u_c = u_g - u_w \geq u_{c\ entry}$). If this capillary pressure u_c exceeds the breakthrough pressure $u_{c\ BT}$, advective gas transport occurs through localised pathways within low-dry-density zones in the sediments. A simplified schematic is shown in Figure 2 [5].

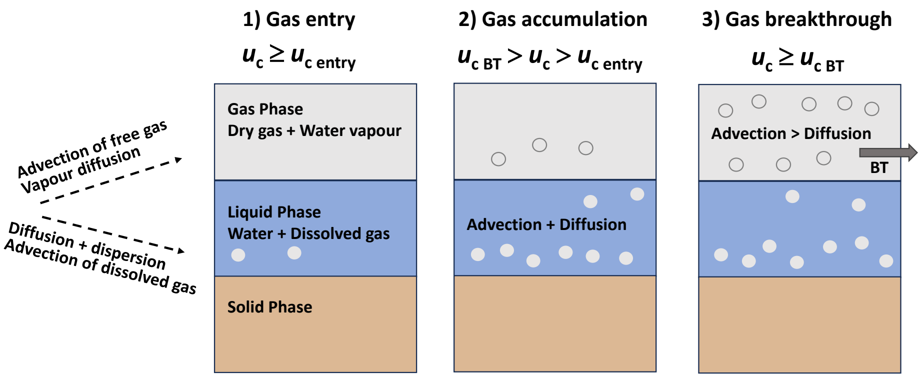

Figure 2. Gas processes and fluxes (adapted from [5]).

The capillary pressure (or matric suction in the context of unsaturated soils) depends on pore size d, the gas-water interfacial surface tension σ_{gw} (assumed equivalent to the air-seawater surface tension at 15ºC: ~75 mN/m), and the contact angle between water and the pore wall θ_w (typically close to 0 in hydrophilic soils). It can be approximated using the Young-Laplace Equation (1). To estimate representative pore sizes, particle-size distributions were used, assuming pore size scales with approximately 0.3 times the particle size of sandy soils [6]. This allows the determination of a preliminary soil-seawater retention curve by associating the finer-percentage passing with the fraction of pores that remain water-filled at a given capillary pressure.

$$u_c = \frac{4\sigma_{gw}\cos\theta_w}{d} \tag{1}$$

To refine this relationship, the van Genuchten model [7] (Equation (2)) expressed in terms of the degree of saturation, S_r, was fitted to the estimated soil-seawater retention curves for two representative soil types: clayey silt and silty sand. Table 1 presents the percentages retained across particle-size ranges (sand, silt, and clay) and the fitted parameters (P_o and λ). Emphasis was placed on fitting the water retention curve to the saturation range of 0.30 to 0.70. Therefore, the table also includes the estimated lower bound of the gas breakthrough pressure, $u_{c\ BTmin}$, evaluated at S_r = 0.50 (the breakthrough propagation pressure exceeds the gas-entry pressure assumed for degrees of saturation between 0.80 and 0.90).

Clayey silts exhibit high gas breakthrough pressures, requiring several tens of kPa to initiate advective gas propagation, whereas silty sands allow gas to propagate at much lower pressures, typically around 13 kPa (Table 1). These differences explain why gas tends to accumulate and propagate beneath fine-grained layers: the barrier imposed by clayey silts prevents upward migration, while the underlying silty sands allow lateral propagation and the formation of connected pathways.

$$S_r = \left[1 + \left(\frac{u_c}{P_0}\right)^{\frac{1}{1-\lambda}}\right]^{-\lambda} \tag{2}$$

This capillary-based framework is essential for interpreting field observations. The persistence of gas pockets beneath clayey silt layers is consistent with high capillary breakthrough pressures, while the ease of gas migration within silty sands aligns with their lower thresholds. The model also provides a basis for estimating the initial gas pressures required to mobilise gas during drilling.

Table 1. Grain size properties and van Genuchten parameters for two soil types.

Soil Type	Sand (%)	Silt (%)	Clay (%)	P_0 (kPa)	λ	$u_{c\ BTmin}$ (kPa)
Clayey silt	2.3	68.9	28.8	5.6	0.2	78
Silty sand	59.6	23.7	16.7	7.8	0.5	13

4 Gas pressure and stress conditions

Gas trapped within the sediment is also subjected to the total vertical stress of the saturated unit weight of the overlying soil. This stress provides an upper bound on gas pressure over liquid pressure, as pore pressures exceeding the total vertical stress would induce pneumatic/hydraulic fracturing or uplift. The vertical stress profile was calculated using representative unit weights ($\gamma_{sat} \approx 18.5$ kN/m³), and hydrostatic pressures were determined from water depths.

To estimate the pressure at which gas begins to propagate into the soil matrix, the capillary breakthrough pressure was added to the hydrostatic pressure at the gas layer depth. This yields an injection pressure that represents the upper bound threshold for gas propagation without fracturing the soil. Because gas is highly compressible, its pressure decreases as it migrates upward; therefore, an average pressure (between the gas injection pressure and the liquid pressure) was used to compute the driving gradient for flow. In addition, at a certain gas pressure over the liquid pressure, a residual capillary pressure (snap-off) is expected to cease advective gas transport [8].

5 Gas flow modelling and effective permeability

Gas escape during drilling is expected to occur through localised pathways, which were modelled using a generalised Darcy-type formulation (Equation (3)). The volumetric flow rate q_g depends on the effective permeability k_{effg}, the gas dynamic viscosity $\mu_g = 1.1\times10^{-5}$ Pa.s (methane at 15ºC and absolute gas pressure 101 kPa), and the pressure gradient (∇z is assumed negligible). The product of the relative permeability k_{rg} and the intrinsic permeability k_{ig} represents the effective permeability to gas, which quantifies the gas phase's ability to flow in the presence of water [8].

Intrinsic permeability to water flow was estimated for the soil types encountered: 10^{-16} m² for clayey silts and 10^{-14} m² for silty sands. The intrinsic permeability for gas was assumed to be 10-100 times that of water (e.g., [9]), and the relative one was equal to 1. The flow path length corresponds to the mean thickness of the gas-bearing layer, typically $L = 0.5$ m. Once gas enters the casing, it rises freely, so all resistance occurs within the soil. The gas pressure gradient ($\Delta u_g/L$) was computed using the difference between the average gas pressure at the inlet $u_{g\ in}$, previously described, and the water pressure at the casing outlet $u_{g\ out}$.

$$
\begin{aligned}
q_g &= -\frac{k_{ig} k_{rg} \rho_g g}{\mu_g} \frac{\nabla u_g}{\rho_g g} = -\frac{k_{effg}}{\mu_g} \nabla u_g \\
q_g &= -\frac{k_{effg}}{\mu_g} \frac{\Delta u_g}{L} = -\frac{k_{effg}}{\mu_g} \left[\frac{u_{g\ out} - u_{g\ in}}{L} \right]
\end{aligned}
\tag{3}
$$

6 Estimation of gas entrapped volumes from field events

Four boreholes with documented gas-escape durations were analysed. Escape times ranged from 7 to 48 hours, and initial gas volumetric flow rates were estimated from the gas pressure gradient and effective gas permeability (Equation (4)). The outflow gas volume V_{out} at constant water pressure at the casing outlet was calculated by integrating the volumetric flow rate over the escape duration, using a casing's cross-sectional area $A = 8.1\times10^3$ mm² for a 4-inch internal diameter.

$$
-\frac{k_{effg}}{\mu_g} \left[\frac{u_{g\ out} - u_{g\ in}}{L} \right] = \frac{1}{A} \frac{dV_{out}}{dt} \tag{4}
$$

Estimated outflow gas volumes V_{out} ranged from 0.2 to 0.9 m³. Assuming a layer thickness of 0.5 m and a volumetric gas content in the sediment of $\theta_g = 0.5$, the corresponding radius of the gas-affected soil ranged from 0.5 to 1.1 m. These values, which are not corrected for the compressibility of the higher average gas pressure at the inlet and do not account for gas dissolved in the liquid phase, provide a first estimate of the gas-affected soil volume and are consistent with the localised nature of gas accumulations observed in the field.

A key finding is that escape duration is the dominant factor determining the estimated gas volume. Longer events correspond to larger volumes, but this relationship does not imply higher in-situ gas pressures. Instead, duration reflects the time required for the soil to progressively close the advective flow pathways as effective stress increases during gas release, a behaviour consistent with observations by [2].

7 Implications for in-situ characterisation

The results demonstrate that current investigation methods are inadequate for quantifying gas in deltaic sediments. Drilling and penetration tests inevitably disturb the stress state, triggering gas release and preventing measurement of in-situ conditions. Geophysical methods such as high-resolution seismic reflection can identify gas-related attenuation zones but cannot quantify gas content or distribution. Crosshole and PS logging provide information on stiffness and wave propagation but are compromised by the need for boreholes, which release gas before measurements can be taken. The unsaturated framework developed here provides a physically based approach for interpreting gas behaviour and estimating gas volumes from field observations. However, it also underscores the need for new in-situ techniques capable of measuring gas content, pressure, and connectivity without inducing stress changes or gas leakage.

8 Conclusion

This study presents a methodology for evaluating the behaviour of gas-bearing deltaic sediments and estimating the volumes of gas released during drilling. The integration of capillary pressure modelling, effective gas permeability assessment, and compressible gas flow analysis provides a coherent explanation of the observed field behaviour in the Llobregat prodelta. Key conclusions include:

- Gas accumulates preferentially within silty-sand layers beneath clayey silts, which act as barriers to gas transport.
- Capillary gas breakthrough pressures vary markedly among soil types, with clayey silts requiring higher capillary pressures to transport gas than silty sands.
- Gas-escape duration is the primary determinant of estimated gas volumes, which range from 0.2 to 0.9 m^3 across the analysed cases.
- Larger gas volumes do not necessarily imply higher in-situ gas pressures.
- Existing investigation methods cannot quantify gas without disturbing the soil; dedicated in-situ techniques are needed.
- The developed framework provides a foundation for future research and supports the design of improved investigation strategies for gas-bearing marine sediments.

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