Relevance of non-uniform dissolved gas concentration in testing gassy soils

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1 Introduction

The presence of gas in soil is an emerging and urgent challenge for both onshore and offshore geotechnical engineering. Degradation of organic matter saturates the pore fluid with dissolved gases (e.g., CO_2, CH_4, H_2S). Under anthropogenic and environmental loading conditions - such as dewatering, loading/unloading, temperature fluctuations, and climate-induced stress [1-3] - these gases exsolve to form free gas bubbles within the soil matrix (Figure 1). These entrapped bubbles can alter the mechanical response of organic clays, peats, and marine sediments, which poses risks to foundation stability [4] and motivates experimental and numerical investigation [5, 6].

Among different laboratory approaches [7, 8], axis-translation combined with pore fluid flushing enables replacement of in-situ pore fluid with gas-saturated water while preserving natural soil fabric and minimising disturbance [9, 10]. Despite its advantages, the resulting spatial uniformity of dissolved/exsolved gas remains unconfirmed. Non-uniform gas distributions may undermine the assumption of laboratory tests as element tests [11], complicating the assessment of the role of gas exsolution on the mechanical behaviour.

This study evaluates the uniformity of gas distribution in peat through new experimental evidence, including local pore pressure measurements. Based on the experimental results, an axisymmetric, fully coupled hydro-mechanical numerical model is developed to simulate the dissolved gas concentration during flushing stages. The findings provide practical guidance for achieving representative element testing under gassy conditions.

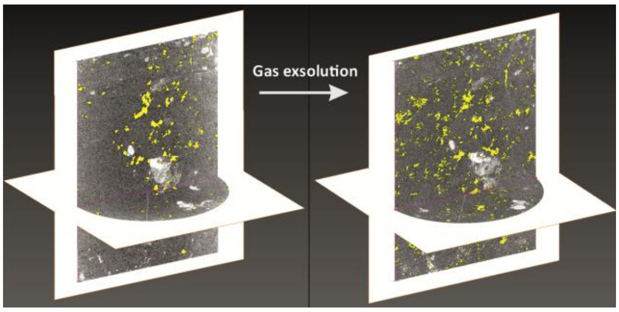

Figure 1. Gas bubbles (highlighted in yellow) within a peat sample caused by gas exsolution, identified via CT image analysis [12].

2 Experimental evidence

A dedicated gassy test was conducted on a natural peat sample (50 mm in diameter and 105 mm in height) using a quasi-dynamic triaxial apparatus. The sample was retrieved from the Leendert de Boerspolder site (Netherlands), with index properties e_0 = 10.80, w_0 = 6.96, G_s = 1.498, $S_{r,0}$ = 0.965, γ = 9.91 kN/m^3. The apparatus includes a cell pressure/volume controller to apply total stress, along with back-pressure and CO_2-saturated water controllers for pore fluid flushing. Conventional pore pressure was measured at the base of the sample through a transducer beneath the porous disk ($u_{f,bot}$ in Figure 2b).

To assess local pore pressure response and dissolved gas distribution, two fibre-optic sensors were installed along the sample (Figure 2a). A fluid pressure sensor was positioned near the top of the sample ($u_{f,top}$ in Figure 2b), following the configuration by Chao et al. [13]. A gas pressure sensor was installed near the base, using a gas-permeable but water-impermeable membrane that allows dissolved CO_2 to diffuse into a small cavity connected to the probe [14].

The testing procedure involved saturation via axis-translation, isotropic compression to 20 kPa, and flushing with undersaturated CO_2-dissolved water under a pressure difference of 2-5 kPa. A total volume equal to three times sample volume was flushed. Gas exsolution was induced by reducing the cell pressure under external undrained conditions with a rate equal to 100 kPa/h. Temperature and humidity were controlled during the test at 14 ± 0.5°C and 68 ± 5%, respectively.

The evolution of the mean operative stress, defined as the difference between cell pressure and measured pore pressure, during gas exsolution is reported in Figure 2b. The pore pressure measured from the base transducer and the local fibre-optic sensor are used to compute the operative stress. The different responses reported in Figure 2b suggest a

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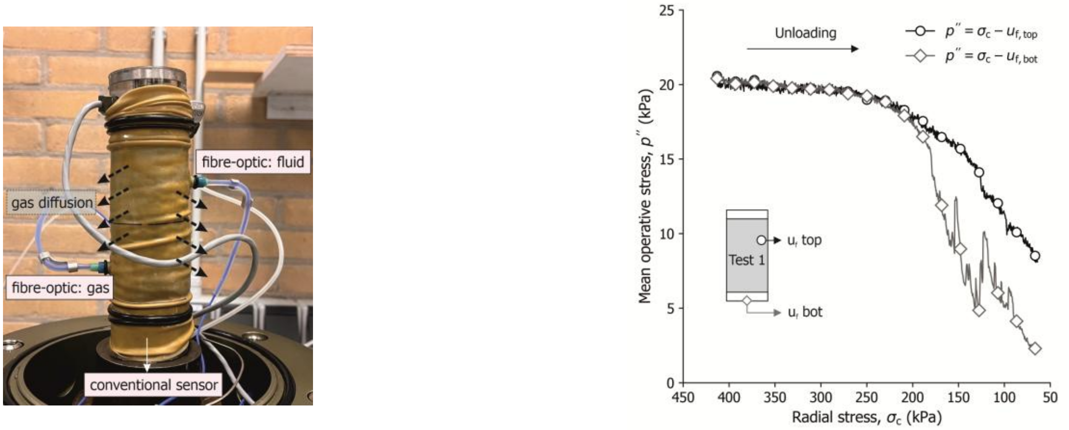
non-uniform pore-pressure profile within the sample, likely due to a gradient in dissolved-gas pressure induced during flushing. The latter can arise from a combination of factors. The fibrous structure of peat promotes variability in gas concentration due to its multi-scale pore network and fibres. In addition, gas diffusion through the surrounding latex membrane into the cell water can generate a concentration gradient along the flow direction, with higher gas content near the inlet than the outlet.

These observations provide experimental evidence of gas concentration gradients along the sample height, which are further examined through numerical modelling incorporating membrane leakage effects.



(a) (b)

Figure 2. Gassy peat test performed in a triaxial apparatus with local pore pressure measurements: (a) the configuration of a gassy sample showing integration of local pore fluid and pore gas pressure transducers; (b) evolution of mean operative stress upon undrained unloading, derived from lateral fluid pressure sensor and bottom conventional pore pressure measurement [11].

3 Finite element model and calibration

Fully coupled three-phase hydro-mechanical simulations were performed in a 2D axisymmetric framework using Code_Bright [15]. Figure 3 illustrates the model geometry, explicitly incorporating the latex membrane (1 mm in thickness). The sample dimensions replicate the experiment, and the gas and the liquid pressure were evaluated in correspondence with the local sensors installed in the sample during the laboratory test, as reported in Figure 3.

The hydraulic boundary B'C', representing the outer edge of the membrane, was assigned a constant dissolved gas pressure of -36 kPa (relative to atmospheric pressure) from gas pressure measurement in de-aired cell water. The mechanical behaviour of the peat sample was modelled using the CASM framework and extended to unsaturated conditions with Bishop stress. The hydraulic properties accounted for gas dissolution-exsolution equilibrium using Henry's law, liquid advection by Darcy's law and dissolved gas diffusion by Fick's law. The corresponding material parameters follow those reported by Xu et al. [11]. The membrane was idealised as a linear-elastic medium, with $E = 1$ MPa and $\nu = 0.499$ [16]. Gas diffusion through the membrane was modelled using the same diffusion coefficients of the soil, while calibrating the membrane porosity, equal to 0.05, based on dissolved gas pressure measurement (Figure 4). Due to the gas concentration gradient between the inner and outer boundaries, gas naturally diffuses from the pore fluid through the membrane in the simulations, thus replicating the experimental conditions.

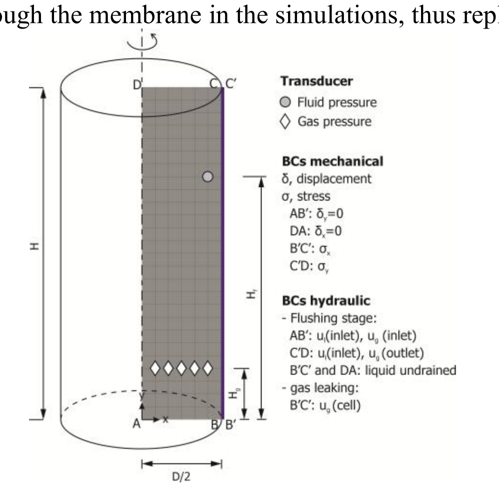


Figure 3. Geometry of the problem adopted in the numerical simulations (sample in grey and membrane in purple).

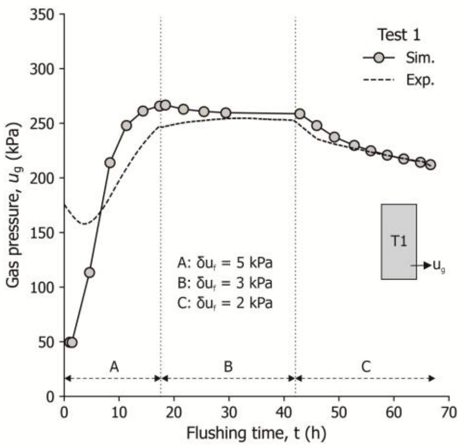


Figure 4. Simulated dissolved gas pressure during pore fluid flushing using calibrated diffusion parameters, compared with experimental measurements.

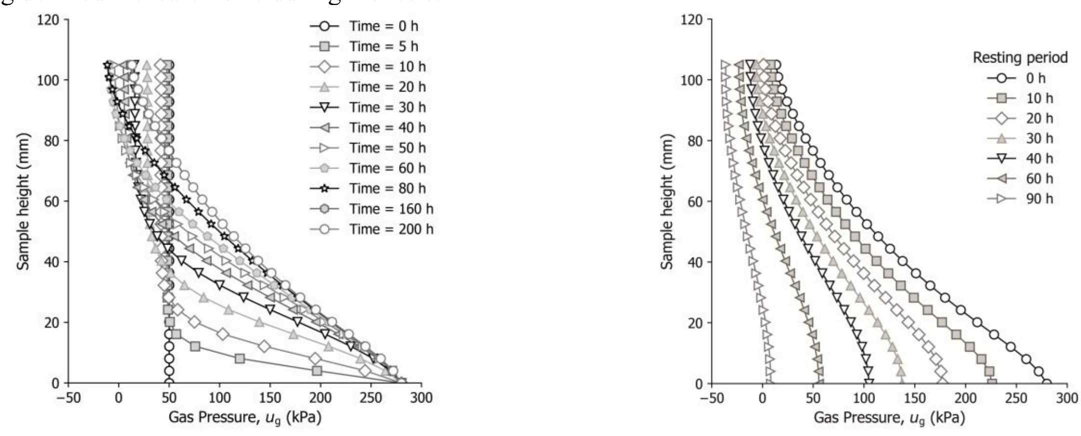
Figure 4 shows the simulated dissolved gas pressure during pore fluid flushing, alongside experimental measurements. The initial 0-10 hours of experimental data show delayed equilibration caused by compression in the interface membrane of the gas sensor. Overall, the gas-leaking model captures the main trend of dissolved gas pressure during flushing. The simulated averaged gas pressure shows changes during stages A, B, and C, reflecting the stepwise adjustments of the pore water pressure difference during flushing, from 5 kPa to 3 kPa and finally 2 kPa. Over stage A, the large pressure difference drives flushing-dominated gas responses, whereas during stage C, the limited flushing pressure leads to gas transport primarily controlled by diffusion through the membrane.

Although local gas pressure measurements provide valuable insight into gas-charging soil behaviour, they do not allow assessment of the gas concentration profile over the full sample height. In this respect, the calibrated numerical model provides a useful tool to explore gas distribution within the sample under varying flushing conditions, enabling optimisation of the procedure.

4 Numerical results

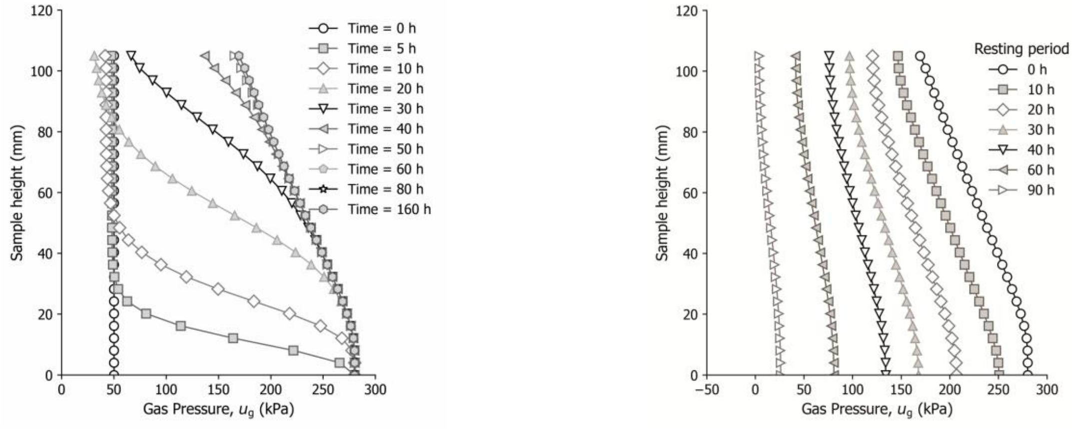
The numerical model is further explored to assess the gas concentration uniformity under different liquid pressure gradients used during the flushing stage and subsequent resting period. Figure 5 and Figure 6 present the dissolved gas pressure profiles during flushing and resting for pressure differences of 2 kPa and 6 kPa, respectively. In both cases, the lower part of the sample responds rapidly to flushing, whereas the upper response is strongly dependent on the applied pressure gradient. At low pressure difference (Figure 5a), the increase in dissolved gas pressure is limited, as the process is dominated by gas leakage through the membrane. In contrast, a higher flushing pressure gradient (Figure 6a) promotes a more uniform gas pressure distribution during the flushing stage. During the resting period, both cases clearly show continued gas loss by diffusion. With time, the sample tends toward a more uniform gas pressure distribution, at the cost of reduced overall gas content due to leakage.

The simulations indicate that while gas diffusion persists throughout the test, non-uniform gas distributions can be mitigated by applying a higher flushing pressure gradient or incorporating an appropriate resting period. The model thus provides a useful tool for evaluating initial gas distributions prior to gas exsolution and shearing stages. It is worth mentioning that although using low gas-permeability membranes could reduce leakage, their increased thickness and stiffness limit compliance and hinder effective sealing around the local pressure sensor installation through the membrane, restricting detailed measurements during the tests.



(a) (b)

Figure 5. Dissolved gas pressure profile in (a) pore fluid flushing and (b) resting period, with flushing pressure difference of 2 kPa.



(a) (b)

Figure 6. Dissolved gas pressure profile in (a) pore fluid flushing and (b) resting period, with flushing pressure difference of 6 kPa.

5 Conclusions

This study investigated the distribution and evolution of dissolved gas in a peat sample during pore fluid flushing through a combined experimental and numerical approach. Laboratory tests incorporating local fibre-optic pressure sensors revealed different pore pressure responses, indicating non-uniform dissolved gas distribution along the sample height. This non-uniformity is attributed to both the intrinsic multi-level pore structure of peat and gas diffusion through the surrounding membrane.

To further examine the leakage-induced non-uniformity, fully coupled hydro-mechanical simulations were performed, successfully reproducing the observed gas pressure trends. The numerical results highlight the critical influence of flushing pressure gradient, circulation duration, and resting period on gas-charging efficiency and uniformity. A higher flushing pressure gradient enhances advective transport, promoting a more uniform dissolved gas profile, whereas low gradients lead to leakage-dominated behaviour. The inclusion of a resting period allows partial homogenisation of gas distribution, although accompanied by gas loss due to diffusion.

The findings demonstrate that achieving representative element-test conditions in gassy soil samples, where gas generation requires a flushing stage, calls for careful control of the flushing strategies. The developed modelling framework provides a valuable tool for optimising laboratory test procedures and assessing initial gas distributions prior to exsolution and shearing. This work contributes to improving the reliability of laboratory characterisation of gas-charged soils relevant to geotechnical applications.

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