Preferential gas pathway formation in Boom Clay under isotropic stress

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1 Introduction

Deep geological repositories (DGRs) are widely considered the reference solution for the long-term management of high-level radioactive waste. In Belgium and the Netherlands, the plastic Boom Clay is being extensively studied as a potential host rock for geological disposal. As a poorly indurated material exhibiting soft-rock behaviour, Boom Clay provides a particularly relevant framework for investigating gas transport in low-permeability geomaterials. Gas will be mainly generated in the repositories due to the anaerobic corrosion of metallic components and the degradation of organic matter. Thus, gas might progressively accumulate, causing an increase in pore pressure, which will influence the hydro-mechanical response of the host formation [1]. If the pressure build-up is sufficient, gas migration may no longer be governed solely by dissolved-gas diffusion and classical two-phase flow, but instead may evolve towards the development of preferential pathways, especially along bedding-controlled heterogeneities and pre-existing discontinuities [2].

Previous laboratory investigations on Boom Clay, especially under oedometer conditions and supported by microstructural analysis, have already provided valuable evidence of strongly coupled hydro-mechanical behaviour during gas injection, including sample expansion, pathway development along bedding planes, and associated changes in permeability [3]. However, under these test conditions, the sample is subjected to zero radial deformation, which may influence the initiation and development of pressure-dilatant gas pathways, particularly when vertical gas flow is parallel to the bedding plane orientation.

As gas transport in such materials is closely associated with the development of pressure-dilatant preferential pathways, an experimental framework that enables less-constrained, displacement-controlled responses is better suited to investigating the initiation and propagation of these pathways under axial- and radial-stress-controlled conditions.

To better capture this behaviour, an experimental campaign has been launched using an isotropic testing cell developed at the Geotechnical Engineering Laboratory of the Universitat Politècnica de Catalunya (UPC). In this setup, the sample first underwent an isotropic loading stress path to reach effective stress under in situ conditions, and subsequently, was subjected to gas injection to induce the opening of preferential pathways. Unlike in oedometer conditions, the sample was allowed to deform laterally, enabling a more realistic representation of pathway development during gas transport.

2 Material

Boom Clay was deposited approximately 36 to 30 million years ago during the Rupelian stage of the Northwest European Tertiary Basin. The samples used in this study were retrieved at a depth of 223 m at the HADES Underground Research Facility (Mol, Belgium). The mineralogical composition of Boom Clay is dominated by 20%–30% kaolinite, 20%–30% illite, 10%–20% smectite, and about 25% quartz and feldspar [4]. The main geotechnical properties, together with the initial testing conditions, are summarised in Table 1.

Table 1. Boom Clay properties and in situ state variables.

Parameter	Symbol	Value
Plastic limit (%)	w_P	27%
Liquid limit (%)	w_L	66%
Density of solids	ρ_s	$2.67\ \mathrm{Mg/m^3}$
Bulk density	ρ	$2.07\ \mathrm{Mg/m^3}$
Void ratio	e	0.58
Water content	w	21.8%
Degree of saturation	S_r	Close to 1
Total suction	s	2.5 MPa

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3 Experimental setup and protocol

A high-pressure isotropic cell, originally developed by Mora Ortiz [5], was updated and modified to carry out the gas injection tests on Boom Clay (Figure 1a). The system can apply up to 10 MPa confining pressure by imposing pressurised water using a pressure/volume controller (PVC). A cylindrical sample with a diameter of 38 mm and a height of 25 mm is placed on a pedestal and enclosed in a neoprene membrane, chosen over conventional latex because of its lower gas diffusion coefficient in liquid.

The hydraulic system was designed to allow independent control of inflow, outflow, and flushing operations. At the bottom of the specimen, the upstream end features separate lines for water injection, gas injection, and flushing, each controlled independently. At the top cap, the downstream lines are used for water pressurisation and gas collection with a PVC. Concentric stainless-steel rings were used as porous stones in both the top cap and the bottom pedestal. A schematic of the modified cell arrangement is presented in Figure 1b.

To monitor the hydro-mechanical response of the sample, a local deformation measurement system [5] was used. This system measures sample displacement at four radial and one axial position using an LVDT at each measurement location. Each unit consists of a spring compressed by a tightening nut that transmits force through a metal coupling to an inner rod, ensuring continuous contact between the rod tips and the sample surface throughout the test, even as confining stress increases.

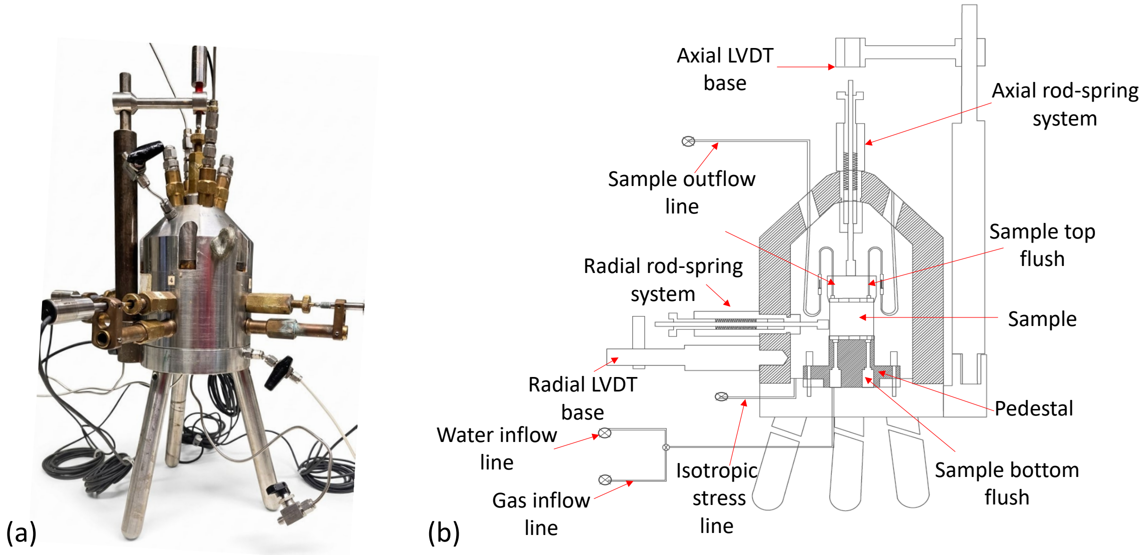

Figure 1. Updated isotropic cell modified after [5]: (a) picture; (b) schematics of the main components.

The testing protocol was equivalent to that reported by [6] for oedometer conditions, intending to compare the hydro-mechanical response of Boom Clay under varying confinements. It consists of three main stages:

- Preconditioning stage: The sample was first loaded under constant water up to 3 MPa at a rate of 15 kPa/min. It was then brought into contact with distilled water at both ends under atmospheric conditions to reduce the matric suction induced on undrained retrieval. Subsequently, water pressure at both boundaries was raised to 0.5 MPa, reproducing a mean effective stress of 2.5 MPa, close to the in-situ stress condition.
- Drained loading stage: The sample was isotropically loaded up to 6 MPa at a rate of 0.5 kPa/min under drained conditions.
- Gas injection and dissipation: Water at the bottom boundary was fully replaced by gas (Helium) at an initial pressure of 0.5 MPa (all liquid was removed from the gas injection system), while the top boundary water pressure was maintained at 0.5 MPa. Gas pressure was then increased to 4 MPa, below the expected gas-entry value for Boom Clay (around 5 MPa), at a constant injection rate of 2 mL/min. After reaching the target pressure, the injection was stopped, and the subsequent pressure dissipation was monitored, while the outflow fluid (liquid and gas) was collected at the top boundary.

In this preliminary study, the bedding orientation of the Boom Clay sample was perpendicular to the upward gas flow.

4 Results

The axial and radial strains computed from the measured displacements are presented in Figure 2a. The results confirm the developed rod-spring system's capability to capture both radial and vertical sample deformations throughout the test. Vertical strain is markedly greater than radial deformation, highlighting the intrinsic anisotropy of Boom Clay linked to its bedding orientation. During the preconditioning stage, the axial/radial strain ratio, $\varepsilon_a/\varepsilon_r$, is approximately 3.3, while it decreased during the drained loading stage to 2.1, which is in agreement with previous studies reporting values in the range of 1.5 to 3 [7]. As the drained loading path approached the yield stress reported below, the initial strain anisotropy tended to decrease with straining, although this needs to be verified by further isotropic loading tests that induce significant plastic deformation.

The corresponding volumetric response is shown in Figure 2b. During the initial pre-conditioning stage, the sample underwent mechanical loading at constant water content to reduce the initial matric suction induced during sample retrieval. The volumetric response recorded during this stage reflected the combined effect of stress increase and matric suction decrease [6].

During the matric suction reduction phase (saturation in the figure), a small compressive response was observed that should be verified with further tests, whereas previous studies under oedometer conditions reported some swelling due to some remaining matric suction kept after the water constant loading [3, 6]. Subsequent water pressurisation induced expansion of the sample, driven by effective stress reduction, with axial strain greater than radial strain. This again highlights the anisotropic response of Boom Clay.

Based on previous studies, the yield stress of Boom Clay is about 6 MPa [3], therefore, the pre-yield compressibility parameter κ = 0.05 was calculated using this curve, which is in good agreement with the value of 0.04 reported by [8].

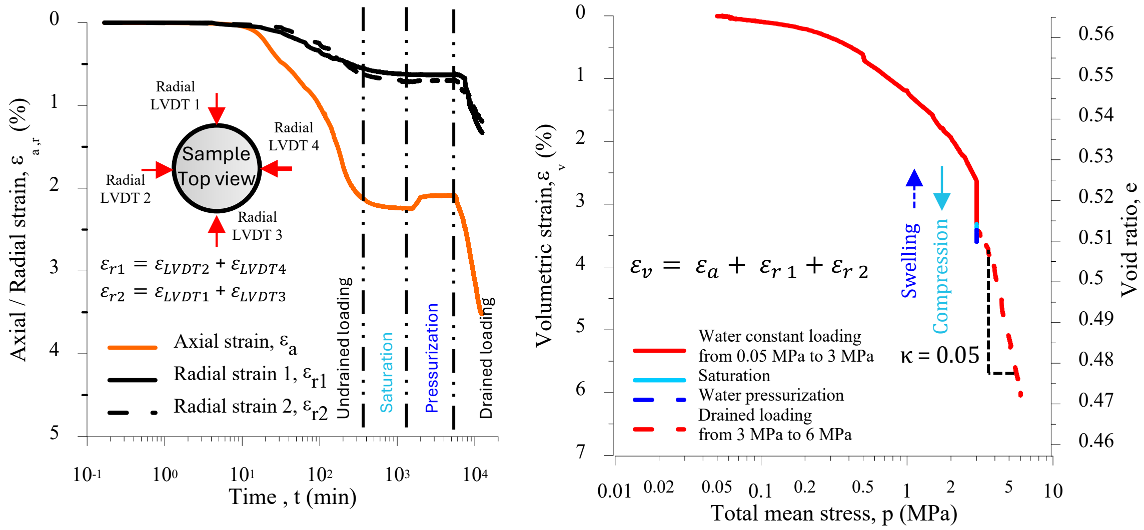

Figure 2. (a) Time evolution of axial and radial strains before gas injection; (b) Stress-strain response before gas injection.

After the drained loading, gas pressure was progressively increased to 4 MPa at a constant injection rate, after which the injection was stopped (shut-off), and gas pressure was allowed to decay under constant volume conditions of the injection line (Figure 3). During the injection phase, the sample exhibited both axial and radial expansion. This behaviour can be attributed to the reduction in net stress associated with the increase in gas pressure. As gas progressively propagated along the bedding planes, local opening of these planes occurred, resulting in sample dilation. Radial expansion was significantly smaller than axial expansion, consistent with the bedding orientation and the inherent anisotropy of Boom Clay. A rapid increase in gas outflow volume occurred at the time of the shut-off, indicating that gas passed through the sample, a phenomenon known as breakthrough.

Following the breakthrough, the sample exhibited both axial and radial compression. As gas pressure dissipated, the net stress increased, leading to progressive closure of the induced pathways and consequent sample compression. The gas pressure dissipation rate after shut-off was approximately -5×10^{-3} MPa/min, decreasing later by one order of magnitude to about -6×10^{-4} MPa/min. This reduction is interpreted as the result of progressive closure of the gas pathways during dissipation. The deformation measurements support this interpretation: immediately after shut-off, compression occurred at a relatively high rate, which then gradually decreased with time. This coupled hydro-mechanical behaviour suggests that gas pathways progressively contracted as gas migrated through the sample, eventually approaching a more stable flow regime.

A notable difference was observed when comparing the present isotropic test with the results reported by Gonzalez-Blanco & Romero [6], in which the sample had the same bedding orientation and was subjected to the same injection rate, but under oedometer conditions. In that study, gas breakthrough occurred after a delay following shut-off. Also, a gas dissipation rate of -3×10^{-5} MPa/min was reported. These differences indicate that radial deformation may facilitate the initiation and propagation of preferential gas pathways within the sample, thereby increasing the gas dissipation rate.

5 Conclusion

This preliminary study investigated gas-induced hydro-mechanical behaviour in Boom Clay using a modified high-pressure isotropic cell for gas injection. The results demonstrate that the developed setup can accurately capture both axial and radial deformations, providing more realistic stress-controlled isotropic conditions for dilatant and preferential gas pathway formation than previous oedometer tests, in which lateral null displacement constraints could affect pathway dilation.

During preconditioning and drained isotropic loading, the deformation response highlighted the marked anisotropy of Boom Clay, attributable to sedimentary bedding planes, with axial strains consistently exceeding radial strains. The estimated swelling index is in good agreement with previous studies.

During gas injection, the sample exhibited dilation in both axial and radial directions, with axial expansion remaining dominant, because the bedding orientation is perpendicular to the axis. Gas breakthrough occurred earlier than in radially constrained tests, indicating that lateral deformability promotes the initiation and propagation of dilatancy-controlled pathways. Following injection shut-off, gas pressure dissipation was accompanied by sample compression and a progressive reduction in the dissipation rate, suggesting gradual closure of the induced pathways toward a more stable flow regime. Overall, the results show that isotropic boundary conditions enhance pathway formation and gas transmissivity, emphasising the importance of stress boundary conditions in the experimental investigation of gas transport in poorly indurated, soft clayey rocks.

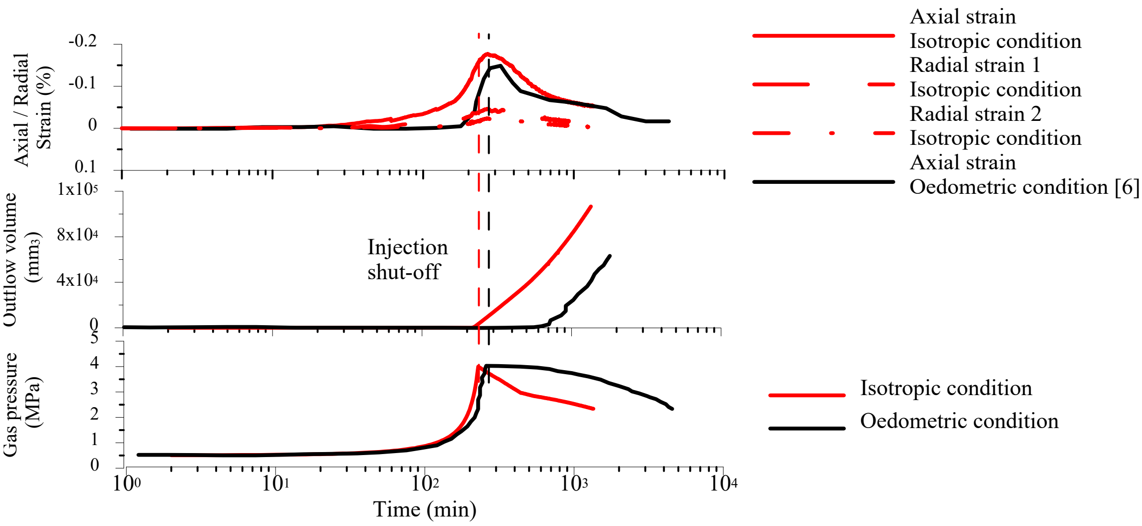

Figure 3. Time evolution of gas inflow pressure, outflow volume and deformations during gas injection and dissipation stage.

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