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Influence of the concentration of dissolved gases in the pore fluid on the saturation behaviour and undrained shear strength of granular soils

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ABSTRACT: Triaxial tests are important, but also complex and time-consuming laboratory experiments for the assessment of soil mechanical properties, whereby achieving complete saturation is particularly lengthy and often requires high saturation pressures. As a result, devices are occupied for a long time or are technically not able to apply the required saturation pressure. The aim of this study is to investigate influences on the saturation behaviour of triaxial samples. Additionally, it aims to determine whether these influences affect the shear behaviour under undrained conditions. In the commonly used backpressure saturation method, pore gas is dissolved in the pore fluid by increasing the saturation pressure. The concentration of dissolved gas in the pore fluid increases during this process, reaching concentrations that exceed the gas concentration at atmospheric pressure. Since it is assumed in triaxial tests that the fluid is incompressible, any resulting influence on the mechanical behaviour remains unaccounted for. This study examined the effect of the conventional backpressure saturation in comparison to a percolating backpressure saturation method, in which degassed or non-degassed water circulates through the sample during saturation. It was also analysed whether the gas concentrations in the pore fluid, affect the mechanical behaviour of the samples. Therefore, the undrained shear behaviour was examined in terms of the friction angle of the instability line and the critical state line. It was shown that using highly degassed water significantly reduces the pressure required to achieve complete saturation for the conventional backpressure saturation. The same effect was observed when utilizing percolating backpressure saturation, whereby no influence of the initial gas concentration in the fluid is evident. Furthermore, the mechanical behaviour of the tested material is not affected by the gas concentration, whereby the authors assume that this is only valid for excess pore water pressure.

KEYWORDS: triaxial testing, saturation, stress-strain behavior, dissolved air.

1 INTRODUCTION

The triaxial test is an essential method for determining soil mechanical and constitutive material parameters. In most cases, a completely water-saturated sample is analysed, whereby the saturation is verified in accordance with internationally valid standards by determining Skempton B-value which represents the ratio of the change in pore water pressure to the change in cell pressure (Skempton, 1954). Typically, B-values above 95% are necessary to fulfil the requirements of the standards proposed in DIN EN ISO 17892-8 and -9 as well as ASTM D4767-11.

The degree of saturation is crucial for the proper estimation of soil properties. Especially for undrained conditions a nearly full saturation of the sample is necessary to induce liquification (Yamamuro and Lade, 1997). Furthermore (Gong et al., 2022) presented a meta-study which clearly shows the reduction of the cohesion and the friction angle of fine grained soils with an increasing degree of saturation. This effect can be explained by additional interparticle forces mainly capillary and adsorptive suction of the pore fluid. These forces are not mobilized due to the shear process and balanced by forces due to interparticle contact (Lu and Likos, 2006).

Aside their influence on mechanical behavior, soil-specific properties influence the time necessary for saturation. The crucial parameters here are the hydraulic conductivity and the initial water content before saturation. Soils with low hydraulic conductivity require more time for saturation (Klute, 2018). Furthermore, soils with an initial degree of saturation of 75% - 85 % require more time for saturation then specimen which are almost dry or almost fully saturated (Black and Lee, 1973). This phenomenon can be attributed to trapped air bubbles in the pore space and pre-existing preferential flow paths (Faybishenko, 1995; Kutter, 2013).

Within this paper the common method of backpressure saturation is addressed (Black and Lee, 1973), alternative methods are summarized in (K. H. Head, R.J. Epps, 2014). Due to backpressure saturation the cell pressure is increased gradually or with a constant rate which assures no critical stresses due to the excess of pore pressure within the sample.

Parameters that influence the duration of this process include the backpressure, the infiltration rate of the pore fluid and the proportion of residual entrapped air in the sample and in the pore fluid itself (Black and Lee, 1973; K. H. Head, R.J. Epps, 2014; Lade, 2016) .

It is known that higher B-values are achieved with increasing saturation pressure. Two phenomena have a complementary effect. Firstly, the entrapped air in the sample is compressed according to Boyle's law. Secondly, the solubility for gases raises due to the increased pressure in the pore fluid, whereby the free pore air is dissolved in the pore fluid in accordance with Henry's law. Due to the increasing solubility of the gas phase with increasing saturation pressure, even initially non-de-aired water has the potential to dissolve the free pore air. Already (Bishop and Eldin, 1950), as well as (Lowe and Johnson, 1960), have provided theoretical relationships that link the initial degree of saturation to the amount of back pressure change needed to fully saturate a specimen, taking Henry's law into account.

In model tests (Kutter, 2013) showed that the infiltration rate significantly influences the degree of saturation. Low infiltration rates lead to capillary saturation, whereby air bubbles are trapped in the sample which, despite higher pressure, cannot be mobilised. This inhibits complete saturation of the sample(Kutter, 2013). The dimensionless capillary number (Ca) is proposed as metric in (Kutter, 2013) and shown in (1). However, local flow paths can influence the fluid velocity, which makes the global evaluation of Ca more difficult (Camps-Roach et al., 2010; Guo, Song and Hilfer, 2022).

Entrapped and free air bubbles in the pore and cell fluid cause measurement errors both in the determination of the volumetric sample deformation in drained tests and in the determination of the pore water pressure change during undrained tests (Tarek Omar and Abouzar Sadrekarimi, 2014). In addition, high degrees of saturation are crucial for investigating both static (Yamamuro and Lade, 1997) and cyclic liquefaction (Yoshimi, Tanaka and Tokimatsu, 1989a; Chavan, Sitharam and Anbazhagan, 2022) in the triaxial test.

The previous studies show the effects of the analysed factors regarding the duration of sample saturation respectively. In the study presented here, these factors are evaluated in terms of their joint effect. An analysis of variance is used to show which factors have a significant influence on the duration of sample saturation and to what extent. In addition to known studies, the influence of the residual dissolved air in the pore fluid on the mechanical behaviour of coarse-grained soils is investigated.

2 THEORETICAL BACKGROUND

2.1 *Saturation*

The saturation of soil samples can be divided into two fundamental mechanisms: infiltration and the dissolution of gases into the fluid. During infiltration, particles are wetted and pore spaces are filled. If possible, the gas phase is displaced; otherwise, compressed. This mechanism dominates when the majority of the pore volume is filled with fluid, which is typically the case in triaxial testing when flushing coarse-grained samples with a low initial water content. The infiltration process is primarily influenced by the viscosity η, surface tension σ, and flow velocity V and quantified by the capillary number Ca and shown in (1).

According to simulations by (Blunt and Scher, 1995), as well as experiments conducted by (Kutter, 2013), the magnitude of Ca can be used as a metric to estimate the extent to which air becomes trapped within the specimen during infiltration. At high Ca, large voids are filled first, followed by smaller menisci. In contrast, at low Ca, where surface tension effects dominate, smaller capillaries are filled first, which can lead to gas entrapment in larger pores.

$$Ca = \frac{\eta \times V}{\sigma} \tag{1}$$

The second mechanism, the dissolution of pore gases into the fluid, forms the basis of the conventional backpressure method (CBM), which is the standard procedure for achieving full saturation of triaxial specimens. This method primarily relies on Boyle's law – which describes an inverse relationship between volume and pressure for ideal gases – and Henry's law, which states that the solubility of gases in fluids depends both on the type of gas and the applied pressure. This pressure dependency is utilized by increasing the absolute pressure while maintaining a constant effective stress on the specimen through simultaneous increases in cell and pore pressure. The method assumes that both the soil particles and the pore fluid are incompressible. As pressure increases, entrapped gas bubbles are compressed, and the potential of the fluid to dissolve gas increases.

The dissolution of gas into the porefluid is a diffusion process which takes time and therefore partially governs the duration of the saturation (Lade, 2016). The rate of these diffusion processes depends on the interfacial surface area and the concentration gradient within the pore fluid (K. H. Head, R.J. Epps, 2014). Figure 1 depicts that as saturation progresses, the gas bubbles become increasingly compressed due to the rising pressure, which significantly reduces the surface area of the gas–fluid interface. As a result, the fluid adjacent to the gas bubble quickly reaches its maximum gas concentration. With ongoing saturation, the concentration gradient within the pore fluid decreases, which in accordence to Fick's laws of diffusion, slows down the transport of dissolved gas away from the interface (Meschede, 2015). It is asumed, that this effect can be counteracted, for example, by continuously exchanging the pore fluid, thereby maintaining or increasing the concentration gradient and thus enhancing diffusion.

Saturation is typically verified using the Skempton B-value, which is determined by increasing the cell pressure under undrained conditions while simultaneously measuring the resulting change in pore pressure. The B-value is defined as the ratio of the measured pore pressure change to the applied cell pressure increment. According to common standards, a B-value of 95% is considered evidence of full saturation. However, this threshold is only conditionally valid, as it is based on the assumption that volume changes must be equal in a closed system.

Therefore, factors like the compressibility of the specimen material or membrane penetration effects, which can influence the relationship between the B-value and the actual degree of saturation, are not taken into account.

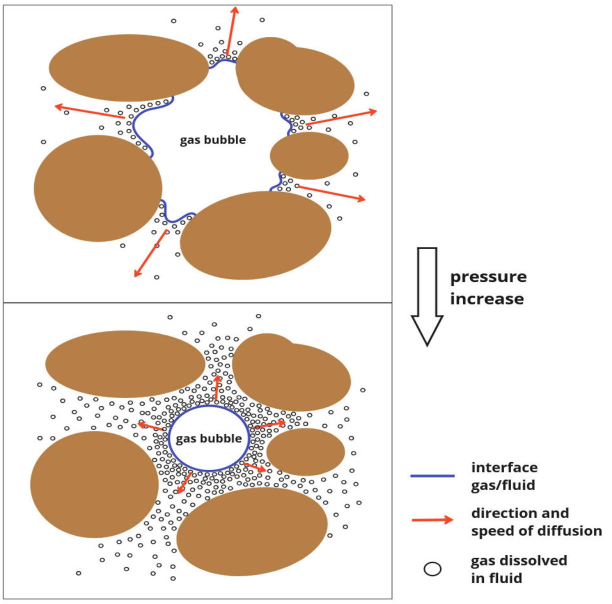


Figure 1 Principle of diffusion and dissolution processes according to Fick's law and Henry's law

2.2 *Shearing CU - test*

In addition to the duration of saturation, the mechanical behaviour of soil samples is influenced by entrapped air, especially under undrained conditions, due to the higher compressibility of air compared to the liquid phase (Yoshikawa and Noda, 2024), which reduces the formation of high pore water pressure. Especially for the estimation of static or cyclic liquification resistance it is crucial to reach B-values close to unity (Yoshimi, Tanaka and Tokimatsu, 1989b).

It is known that the small strain stiffness and the dynamic shear modulus increases with decreasing saturation (or increasing matric suction). Whereby the effect is more pronounced for the small strain stiffness (Ghayoomi, Suprunenko and Mirshekari, 2017; Gu et al., 2021). To evaluate the influence of the pore fluid on the overall stiffness, Bender element tests are carried out and the P-wave velocity is determined (Gu, Yang and Huang, 2013; Gu et al., 2021). For non-degassed water, a directly proportional relationship between the P-wave velocity and the B-value was found whereas (Gu, Yang and Huang, 2013) found no dependencies when using degassed water. It is assumed that the inhomogeneity in the distribution of free pore air is greater when using non-degassed water, which means that the stress-dependent compressive stiffness of the soil skeleton is measured rather than that of the fluid phase (Gu et al., 2021; Astuto et al., 2023).

With regard to strength, a decrease in load-bearing capacity was observed in water-saturated clay samples under triaxial compression and extension when using non-degassed water (Murray and Tarantino, 2019). The authors postulate that possible cavitation of the gas phase as pore water pressure decreases can lead to local shear failure, which reduces the global shear strength. The necessary negative pore water pressure to induce cavitation is modelled for silt in the range of 100 to 2,200 kPa (Luo, Likos and Lu, 2021). A possible influence due to cavitation is therefore particularly evident in dense samples which are completely saturated, whereby, in contrast to unsaturated soils, a reduction in bearing capacity is provoked. The effect of cavitation may increase with increasing gas concentration in the fluid. Fluids with dissolved gases are much more susceptible to cavitation (Li, Gu and Chen, 2017). This cavitation can lead to a change in shear strength and overall stress absorption (Murray and Tarantino, 2019).

For granular soils (Irani et al., 2025) demonstrated that the friction angle in dense samples can be up to 10° lower under undrained conditions compared to drained conditions. This difference decreases as the density decreases. The authors attribute this to the limited volumetric deformation that occurs under undrained conditions, which results in reduced friction mobilization. Additionally, considering the potential for cavitation, this factor might further contribute to the observed differences in results.

3 METHODOLOGY

The aim of this study was to investigate whether the initial gas concentration of the pore fluid and the infiltration rate, at which it is introduced into the specimen, influence the saturation behaviour. Additionally, the study sought to determine whether a modified backpressure method – in which the specimen is continuously percolated with fluid – achieves full saturation more rapidly than the conventional backpressure method. Furthermore, the study examined whether the final gas concentration remaining in the pore fluid influences the shear behaviour of the specimen.

For the experiments a gravel-sand mixture was used. Figure 2 shows the particle size distribution. The specimens were prepared at a gravimetric water content of 2% in five layers using the moist tamping method, resulting in a porosity of n = 0.382. The parameters investigated are summarized in table 1.

At the beginning of each test, the specimens were stabilized using an effective confining pressure of 30 kPa. Subsequently, the specimens were flushed through from bottom to top with fluid at one of the examined infiltration rates. The volume of fluid introduced corresponded to twice the specimen's pore volume. After flushing, the pore water pressure was increased to limit the effective stresses acting on the specimen to 10 kPa.

Table 1 Experiments conducted.

Test series	saturation method [-]	gas concentration [%]	infiltration rate [ml/s]	Type of shear test
1	CBM_{gas}	100	0,5	-
	CBM_{gas}	100	0,225	-
	CBM_{gas}	100	0,05	-
	$CBM_{degassed}$	15	0,5	-
	$CBM_{degassed}$	15	0,225	-
	$CBM_{degassed}$	15	0,05	-
2	PBM_{gas}	100	-	CU
	$PBM_{degassed}$	15	-	CU

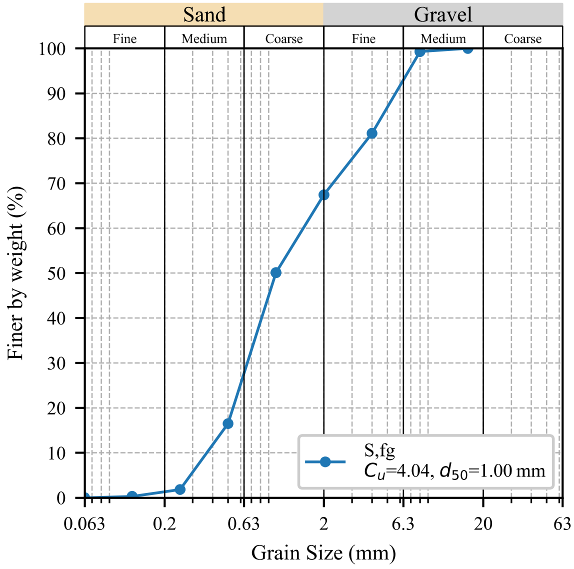


Figure 2 Particle size distribution of the material tested.

In the first test series, the influences of the gas concentration in the fluid supplied to the specimen, as well as the effect of varying infiltration rates on the saturation behaviour, were investigated. The pore fluid was de-gassed utilizing vacuum, and care was taken to prevent air-contact of the pore fluid bevor flushing the sample. The residual gas concentration within the pore fluid was 15%. The gas concentration was assessed based on the oxygen content in the fluid, which was quantified using an optical sensor. Saturation was performed with the conventional backpressure method (CBM) using pressure steps of 50 kPa and 100 kPa. After each pressure step, a B-value was determined to evaluate the degree of saturation.

In the second test series, the influence of continuous percolation of the pore fluid during saturation at varying gas concentrations, was investigated. Additionally, the effect of gas concentrations resulting from the different saturation methods on the shear behaviour was examined. The stabilization and flushing of the specimens as well as the verification of the gas concentration of the supplied pore fluid was carried out the same like in the first test series. During flushing, the infiltration rate was fixed at 0.225 ml/s. Subsequently, the specimens were saturated with the percolation backpressure method (PBM) using a pressure ramp of 5 kPa/min. To ensure sufficient percolation, a hydraulic gradient of 2 kPa was applied. The degree of saturation was verified by B-value tests at confining pressures of 300 kPa, 500 kPa, 600 kPa, and 700 kPa.

After saturation, the specimens were subjected to effective consolidation pressure of 100 kPa, 200 kPa, and 400 kPa. Following the stabilization of volume change below 0.1 ml/h, the specimens were shear tested under undrained conditions at a controlled strain rate of 2.4 %/h.

The B-values of each series were analysed by means of analysis of variance (ANOVA) for the individual pressure steps, with particular focus on achieving the normative threshold B-value of 95%. The results of the B-tests were compared with those saturated by CBM.

To investigate the influence of gas concentration in the pore fluid on the mechanical behaviour, the stress paths in the p′–q space were interpreted, and the friction angles of the critical state line (CSL) and the instability line (ISL) were calculated using Eq.2 (Lade, 1992) and compared.

$$\sin \varphi' = \frac{3M_c}{6 + M_c} \tag{2}$$

The specimens' tendency for volumetric change was assessed by analysing pore pressure changes (Δu) as a function of axial strain (ε_1)

4 RESULTS

4.1 *Saturation*

For the first test series utilising the CBM, no significant influence of the infiltration rate on the saturation behaviour was observed. The influence of the infiltration rate is only of significance during early stages of saturation and negligible for high B-values. In contrast to this, the gas concentration in the pore fluid had a statistically significant impact throughout the entire saturation process.

Figure 3 compares the measured saturation behaviour of the CBM and the PBM samples for high and low gas concentrations in the infiltrating fluid. Since it was found that the infiltration rate had no significant influence on the results, all test series of the CBM from table 1 were used for data analysis. It can be observed that for saturation with CBM a substantially lower saturation pressure was required to reach a B-value greater 95% when using fluid with reduced gas concentration. On average, the pressure needed to reach the B-value > 95% was approximately 150 kPa lower for the tests conducted with low gas concentration in the pore fluid.

Utilizing PBM also reduces the saturation pressure necessary to reach a B-value > 95%. However, for PBM the gas concentration in the infiltrating fluid only showed a measurable influence for lower saturation pressure. From 500 kPa onwards, no significant differences in the degree of saturation were detected. Consequently, no effect of the gas concentration in the pore fluid could be observed for the PBM.

4.2 *Shear behavior*

As shown in Figure 4(a-b), the pore pressure evolution during shearing lies within the same range of scatter for both high and low gas concentration. This shows that for the samples with a porosity of n=0.382, there is no detectable influence of residual pore air on the development of pore water pressure. Only the scatter of the pore water pressure measurement is slightly greater for degassed water.

The mechanical behaviour in the p′–q domain is shown in figure 4(c-d). Herein, the mean value and the scatter of the three subsamples for the investigated consolidation stresses of 100 kPa, 200 kPa and 400 kPa are shown. The instability line and the critical state line were evaluated using the mean value of the tests. The corresponding friction angles were calculated using (2), assuming $c' = 0$. The mean friction angles for the test with high gas concentration in the pore fluid are $\varphi'_{ISL} = 25.3°$ and $\varphi'_{\mathrm{CSL}} = 33.3°$ and just slightly higher than the averaged friction angles for lower gas concentration in the pore fluid with $\varphi'_{\mathrm{ISL}} = 24.7°$ and $\varphi'_{\mathrm{CSL}} = 32.6°$. Based on these results, no significant influence, of the gas concentration in the pore fluid, on the shear behaviour was observed.

5 DISCUSSION

5.1 *Saturation*

The infiltration rate had no significant influence on the saturation behaviour within the investigated range. Consequently, the simulation results of (Blunt and Scher, 1995), as well as the experimental findings of (Kutter, 2013), could not be transferred to the saturation behaviour of triaxial soil specimens. This can be partially explained by the fact that the influence of the capillary number (Ca) through infiltration rates could only be indirectly assessed, and the variation of infiltration rates was limited by constraints determined in preliminary tests. Further increases in the infiltration rate would have had a significantly increased risk of hydraulic failure of the specimens due to the excess of pore water pressure. Lower infiltration rates are of no significance for laboratory purposes. In contrast, an influence of the gas concentration in the supplied pore fluid on the saturation behaviour could be demonstrated for CBM, allowing a reduction of the required saturation pressure by 150 kPa. Considering the additional potential for gas absorption in the degassed fluid as described by Henry's Law, it is notable that this effect exceeds the pressure potential created by degassing (approximately 90 kPa) by 60 kPa. This may indicate that the gas absorption potential in the pore fluid is not fully exhausted, but further gas sorption is significantly slowed due to the decreasing concentration gradient.

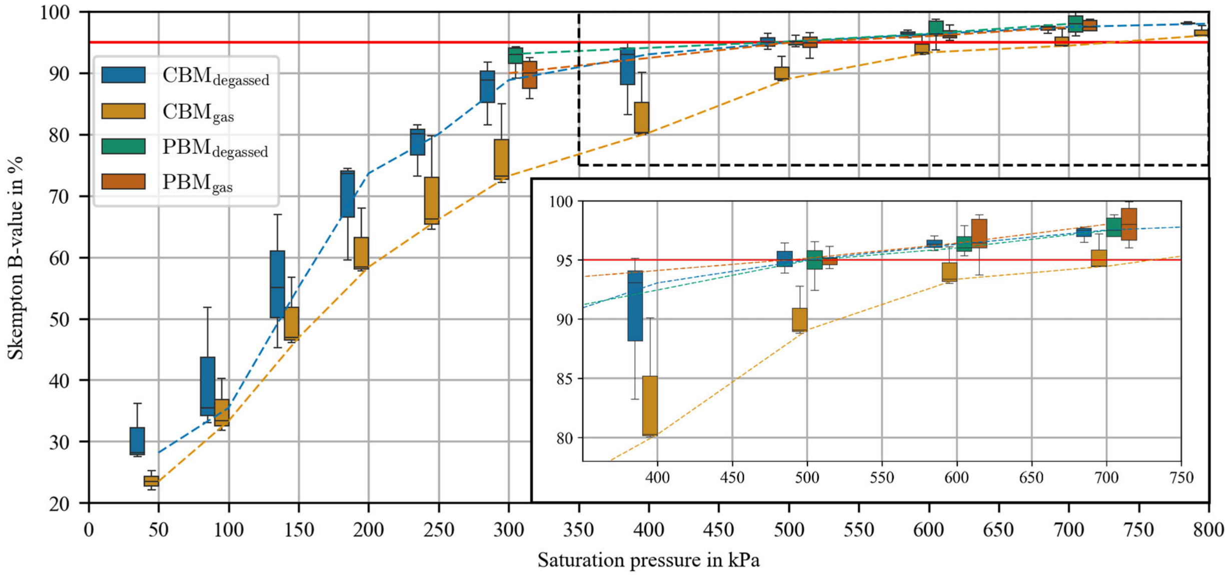
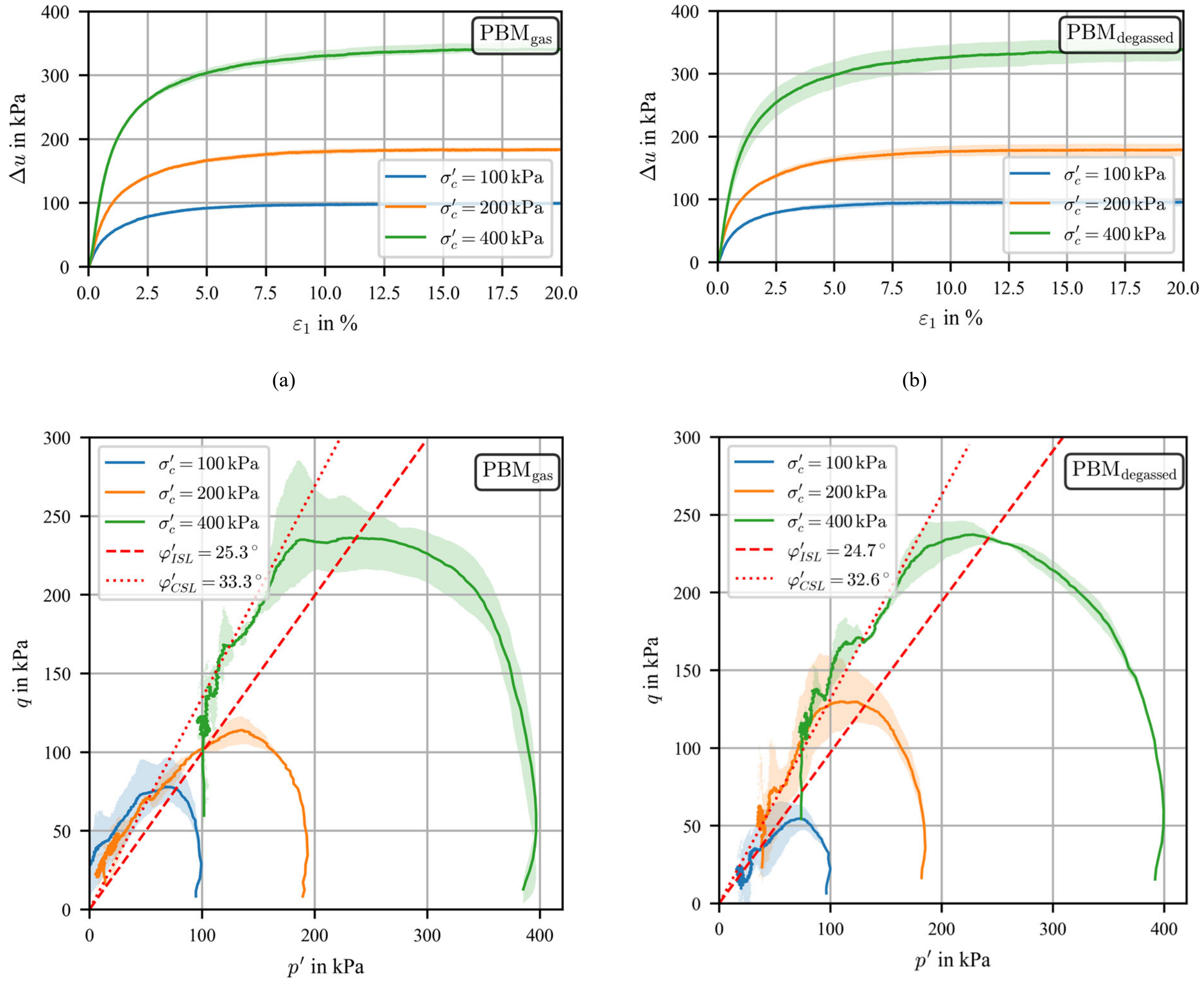


Figure 3 The development of the B value for the examined test series according to table 1. The median value is shown as line plot with its corresponding interquartile range as box plot.



(a)

(b)

(c)

(d)

Figure 4 The mechanical behavior of the soil tested with varying gas concentrations in the pore fluid, with figures (a) and (c) summarizing the results with high gas concentrations and figures (b) and (d) the results with low gas concentrations. The mean value from three separate tests (line) and the corresponding scatter (area) are shown in each case. In (a, b), the change in pore water pressure is shown as a function of axial strain. In (c, d), the stress paths in p'-q domain and the corresponding mean friction angles of the instability line and the critical state line are compared.

Investigating how gas concentration changes with exposition time affects the B-value could enhance understanding of the potential of degassed water for saturation.

The demonstrated influence of flow through the specimen utilizing PBM on the saturation behaviour supports the assumption that the concentration gradient in the pore fluid affects the saturation time up to a certain point. The possible acceleration of the saturation process based on the concentration gradient in the pore fluid appears to be largely achieved by degassing the injected fluid in the conventional backpressure method. Since neither percolation with non-degassed nor with degassed water through the specimen led to a further acceleration of saturation beyond this point.

5.2 *Shear behavior*

The influence of different gas concentrations on the stiffness of the pore fluid or the soil skeleton could not be determined. Neither in the $\epsilon_1 - {\sigma_1}'$ curves (not shown) nor in the build-up of pore water pressure (figure 4 (a-b)). Thus, the finding of (Gu, Yang and Huang, 2013) that the use of degassed water leads to nearly constant P-wave velocities despite different B-values cannot be transferred to the mechanical behaviour of a granular soil under large shear strain, since the observed pore water pressure build-up is very similar irrespective of the gas concentration, the scatter for samples with degassed water is greater than for samples without degassed water.

With regard to the bearing capacity of the soil, both the instability line and the critical state line, shows no significant influence of the gas concentration. It is assumed that the concentration of gas in the pore fluid can affect the shear behaviour, especially when cavitation occurs in the pore fluid due to sufficiently high negative pore water pressure caused by shearing. Effects are to be expected in particular for the interpretation of the CSL. Negative pore water pressures were not observed as medium dens samples were investigated in this study. Therefore, the authors can conclude that the mechanical behaviour of a granular sample is not influenced to a relevant extent, by gas concentration in the pore fluid if the change in pore water pressure is positive but probably could be, if the change in pore water pressure is negative.

Apart from the mechanical behaviour, no significant influence of the gas concentration in the pore fluid on the accuracy of the pore water pressure measurement could be detected that could not be attributed to other influencing factors, such as slightest global or local porosity variations, which can strongly influence the mechanical behaviour (Lipiński, Wdowska and Puspitaningrum, 2023).

6 CONCLUSIONS

Based on the experiments conducted in this study, the following conclusions can be drawn regarding the saturation behaviour:

- Low gas concentration in the pore fluid reduces the saturation pressure when using the CBM by 150 kPa
- The use of the PBM leads to similar reduction for the required saturation pressure.
- The effects of reducing the gas concentration in CBM or utilizing PBM are approximately equal in magnitude.
- The gas concentration in the pore fluid does not influence the saturation pressure required to achieve a 95% B-value when using PBM.
- The shear behaviour of materials with positive pore water pressure build up is not influenced by the gas concentration in the pore fluid, neither in terms of friction angles nor in the exceed of the pore pressure.

Further investigations are recommended to improve the understanding of the saturation process, especially regarding the exposition time of the fluid-gas-phase in the sample. Additionally, the authors assume that a high gas concentration in the pore fluid may increase the risk of cavitation during shear loading under negative pore water pressure changes. Therefore, further investigations on dense specimens are necessary.

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