# An insight on the experimental volumetric behaviour of gassy soils

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**Abstract.** Induced Partial Saturation (IPS) is one of the most innovative and promising countermeasures to mitigate soil liquefaction risk. Mechanical benefits of air/gas bubbles occluded within the pore water have been studied in the last decade through undrained cyclic tests on *quasi*-saturated (gassy) soils, demonstrating that the increased pore fluid compressibility prevents liquefaction triggering. The greater compressibility of the air bubbles rules the volumetric strains of gassy soils during seismic shaking reducing the build up of the pore water pressure. Mele et al., (2022) verified that, at the laboratory scale, due to lower frequencies of the applied cyclic loads, a non-negligible amount of soil volumetric strains is due to dissolution of air bubbles in the water ($\varepsilon_{v,diss}$). The outcomes of some simple compression tests carried out on a two-phase medium made of air/water confirm that such amount cannot be correctly computed with the Henry's law, which considers the dissolution process of air into water in the hypothesis of continuous air phase. Experimental evidences highlighted that $\varepsilon_{v,diss}$ is mainly ruled by the continuity of air phase (linked to the chosen experimental procedure), and it exceeds the theoretical previsions when air phase is discontinuous with single bubbles occluded in the fluid phase.

## 1 Introduction

Liquefaction is a phenomenon marked by a rapid loss of shear strength and stiffness, which can occur in loose, saturated sandy soil deposits subjected to earthquakes or other forms of rapid loading. During liquefaction, when the effective stresses approach zero, soil behaviour switches from that of a solid to that of a fluid [1 - 3]. Since in this transient state the soil behaves as a fluid, liquefaction is a relevant cause of damage to structures and infrastructures during earthquakes, as happened in several places hit by this phenomenon, such as Niigata (Japan) in 1964, Christchurch (New Zealand) in 2011, Emilia Romagna region (Italy) in 2012 or a most recent case in Indonesia in 2018. Therefore, it is of the outmost relevance to identify mitigation techniques able to tackle the risk and satisfying the requisites of soundness and reliability in design, environmental compatibility and cost effectiveness.

The mitigation actions belonging to the family of ground improvement techniques (i.e. those concentrating on the ground and not on the foundations of structures) may modify soil density [4], composition [5 – 8], water flow patterns (drainage; [9]) or the degree of saturation (induced partial saturation, IPS; [10]) of liquefiable soil. For long time soil densification has been used as the main mitigation technique against liquefaction. Although very simple to apply, the compaction cannot be easily adopted in urban areas, where the mitigation interventions should avoid disturbing existing buildings and constructed facilities. It becomes necessary to adopt less invasive mitigation techniques that combine the need to reduce the risk of liquefaction and the protection of the safety condition of the existing buildings.

From this point of view, Induced Partial Saturation (IPS) seems to be the most innovative and promising techniques against liquefaction, due to its low-cost, eco sustainability and its applicability in the closely constructed residential areas. Several methods to introduce air/gas bubbles into pore water have been reported in literature, the main are: air injection, biogas produced by bacteria in the soil, electrolysis, sand compaction pile and chemical methods to produce tiny gas bubbles in-situ from nutrients.

When partial saturation is induced into a soil volume, high degrees of saturation Sr are expected with occluded bubbles into a continous water phase (gassy soils). Even though the degree of saturation from which the gas phase is discontinuous depends on soil grading, generally a reference value Sr=80% is considered, as reported by Tsukamoto et al. [11]. From a mechanical point of view, although air ($u_a$) and water ($u_w$) pressures differ (the difference depending on the size of the bubbles), in gassy conditions there is no mechanical effect of suction ($s=u_a-u_w$) on the soil skeleton, and so the principle of effective stresses - in its traditional form – can be still assumed to hold [12].

The effectiveness of IPS has been widely demonstrated at small [13 – 17] and large scale [18 – 20].

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The increase of undrained cyclic resistance of gassy soils - compared to the saturated ones - is linked to the high volumetric compressibility of the gas/air bubbles, which reduces the increase of pore water pressure Δu during seismic shaking [21 - 22]. Unlike saturated soils where volumetric strains ($\varepsilon_v$) are nil in undrained conditions, gassy soils exhibit $\varepsilon_v$ during the undrained cyclic phase, being air phase more compressible than fluid phase. The volumetric strains of partially saturated soils were measured during the cyclic loading phase by Mele et al., [15] and Mele et al. [16], who used a cyclic triaxial cell with a double-cell system [23]. It can be noted (Fig. 1) that, during the cycles, $\varepsilon_v$ increases with a rate that resembles that of the excess pore water pressure Δu. It confirms, once again, the link between the excess pore pressure build-up with the induced volumetric strains and then with the compressibility of the fluid phase.

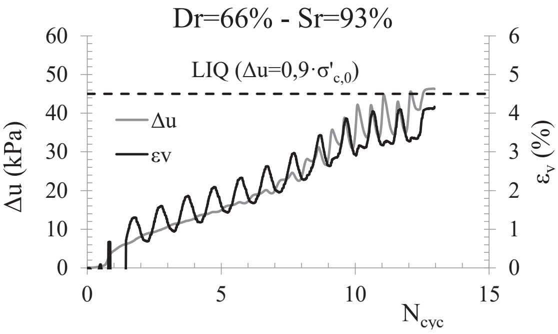



**Fig. 1.** Excess pore pressure and volumetric strains of a cyclic triaxial test performed by Mele et al., [16] on Pieve di Cento sand.

In laboratory to avoid backlash phenomena during stress reversal, the frequencies of the applied cyclic loads are usually lower than 0.5 Hz. In these conditions the volumetric strains are due not only to the compressibility of fluid phase but also to the dissolution of air bubbles into water. Based on the experimental results, Mele et al. [16] stated that the continuity of air phase (linked to the induced value of Sr) could influence the dissolution phenomena of air within the fluid phase.

The paper is involved in this framework, with the main aim to deepen investigate the role of the air dissolution process in the experimental volumetric response of gassy soils.

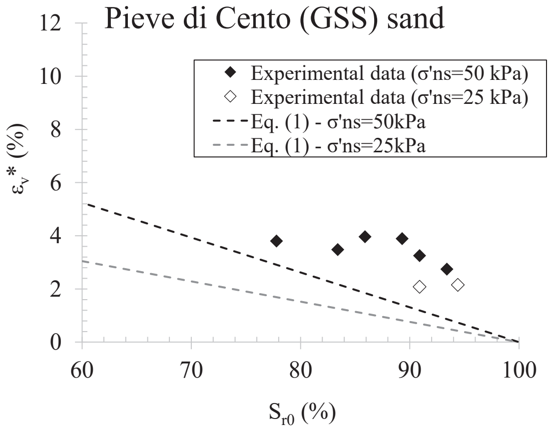
## 2 Experimental evidences

As stated by Okamura & Soga [21], the cyclic behaviour of quasi-saturated soils can be predicted through the potential volumetric strain ($\varepsilon_v$*), that is the maximum soil volumetric strain reached when the effective stresses become nihil (i.e., $u_a=u_w=\sigma$). The potential volumetric strain, due to the compressibility of the fluid phase, can be quantified by applying the Boyle and Mariotte's law (PV=const) and it is given by:

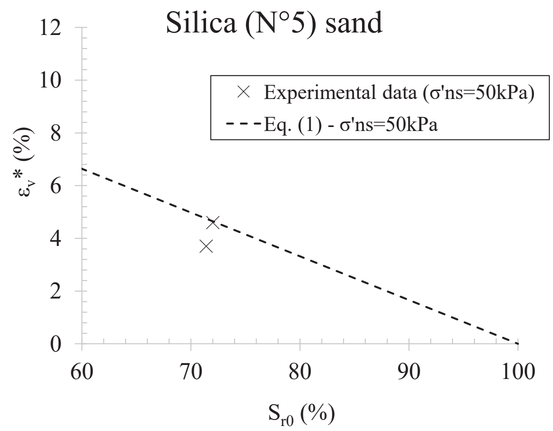
$$\varepsilon_v * = \frac{e_0}{1+e_0} \cdot (1 - S_{r0}) \cdot \left(1 - \frac{u_{a,0}}{\sigma}\right) \tag{1}$$

where $e_0$, $S_{r0}$ and $u_{a,0}$ are the initial void ratio, degree of saturation and pore air pressure, respectively, and σ is the total stress.

Mele et al. [16] showed that for high values of $S_r$, eq. (1) underestimates the measured volumetric strains (Fig. 2a), while it seems to match the experimental data for lower degrees of saturation (Fig. 2b).




(a)




(b)

**Fig. 2.** Potential volumetric strain ($\varepsilon_v$*) versus the initial degree of saturation: experimental data and theoretical correlation [Eq. (1)] for (a) Pieve di Cento (GSS); and (b) silica (N°5) sands [16].

Mele et al. [16] attributed this discrepancy to the occurrence of air dissolution into water during the loading phase, which is not taken into account in eq. (1), which only considers the compression process of bubbles subjected to an increase of pressure.

The increase of pressure in the bubbles during cyclic loading increases gas solubility (in accordance to Henry's law), and therefore a gas flow from the bubbles to the water is triggered with a subsequent further reduction of the bubbles volume. The gas flow is ruled by Fick's law, which describes the time taken by a solute to transfer into solution due to a concentration gradient in three directions ($\frac{\delta C}{\delta x}$; $\frac{\delta C}{\delta y}$; $\frac{\delta C}{\delta z}$), given by:

$$\frac{\delta C}{\delta t} = D \cdot \left(\frac{\delta^2 C}{\delta x^2} + \frac{\delta^2 C}{\delta y^2} + \frac{\delta^2 C}{\delta z^2}\right) \tag{2}$$

where D is the diffusion coefficient.

The amount of gas which dissolves over time within the fluid phase is related to the adopted loading frequency: the lower the load frequency, the higher such amount and therefore the related soil volumetric strains. The experimental evidences (Figs. 2) seem to indicate that the effect of load frequency is more significant at high degrees of saturation ($S_r$>80 %). In this condition, the air phase is certainly discontinuous with occluded bubbles dispersed within the fluid phase.

In Figure 3, the ratio between the experimental ($\varepsilon_{v;exp}$*) and the theoretical ($\varepsilon_v$*; [Eq. (1)]) values of the potential volumetric strains have been plotted for five tested sandy soils versus the initial degree of saturation ($S_{r0}$). Although data pertain to soils with different gradings ($0.115 \leq D_{50}(mm) \leq 0.471$; $0 \leq FC(\%) \leq 40.6$; $1 \leq C_u \leq 400$) and state conditions (25 kPa ≤ $\sigma'_{0ns}$ ≤ 58 kPa; $0.58 \leq e_0 \leq 1.22$), a unique relationship seems to exist between $S_{r0}$ and $\varepsilon_{v;exp}*/\varepsilon_v*$. It can be observed that, for Sr< 0.80, the results of laboratory tests were unaffected by the air dissolution into the water, and Eq. (1) can be used to correctly compute the potential volumetric soil strains. In this range, both water and air phases are continuous.

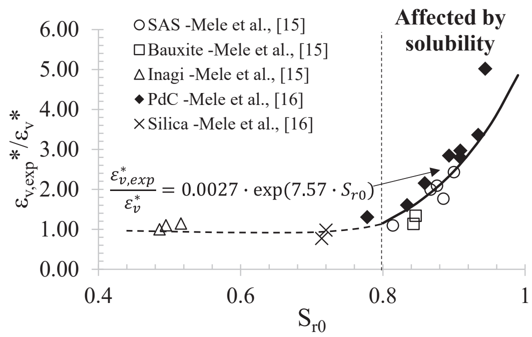



**Fig. 3.** Ratio between the experimental values of final volumetric strains ($\varepsilon_{v;exp}$*) and the theoretical values ($\varepsilon_v$*; [Eq. (1)]) versus the initial degree of saturation ($S_{r0}$) (modified from Mele et al., [16]).

## 3 Some insight into mechanisms

Generally speaking, in a gassy soil with occluded bubbles made of an ideal gas, the total soil volumetric strain ($\varepsilon_v$) induced by an undrained cyclic load may be seen as the sum of two components:

$$\varepsilon_v = \varepsilon_v^* + \varepsilon_{diss} \quad (3)$$

where $\varepsilon_v$* is the component due to the compressibility of fluid phase (eq. 1) and $\varepsilon_{v,diss}$ represents the further component of the volumetric strain induced by the gas dissolution into the water. Gas dissolution is ruled by Henry's law, which states that the gas pressure $P_g$ (partial pressure when a single gas species is taken into account) is directly proportional to the concentration of gas in the water phase $C_a$, through Henry's constant $k_H$, according to the following equation:

$$P_g = k_H \cdot C_a \quad (4)$$

Air is generally composed by 80% of nitrogen ($N_2$) and 20% of oxygen ($O_2$). While the former is characterized by a very low solubility ($k_H$=1474 l·atm/mol, T=20 °C), the latter has a high solubility into water ($k_H$=743 l·atm/mol, T=20 °C). The volumetric strain due to dissipation ($\varepsilon_{v,diss}$) can be found from eq. (3). $C_a$, expressed in mol/l, can be evaluated assuming $P_g$ (partial pressure) as $0.2 \cdot (u_w + p_a)$ for $O_2$ and $0.8 \cdot (u_w + p_a)$ for $N_2$ (absolute pressure). Known $C_a$ and the volume of water, number of moles of oxygen ($n_{O2}$) and nitrogen ($n_{N2}$) that solubilize into water may be easily computed. The corresponding volume change induced by moles of $O_2$ and $N_2$ that solubilize into water may be evaluated by means of the Law of Ideal Gases:

$$P \cdot V = n \cdot R \cdot T \quad (5)$$

where R is the gas constant (8.31 J/mol·K) and T is the temperature assumed 293.15 K (20 °C).

Once the volume change induced by dissolution is known for oxygen and nitrogen, the volumetric strains induced by dissolution ($\varepsilon_{vdiss}$) can be computed for all the tests as the sum of $\varepsilon_{diss,O2}$ and $\varepsilon_{diss,N2}$. As stated by Mele et al. [16], the prevision of $\varepsilon_{v,diss}$ given by eqs. 4 and 5 is strictly affected by the adopted values of $k_{H,}$ ($k_{H,O2}$ and $k_{H,N2}$).

Compared to an ideal two-phases medium, in which both water and air are continuous phases (Fig. 4a), in *quasi*-saturated soils the gas phase is discontinuous (Fig. 4b) and therefore dissolution process is also ruled by the dimension of the bubbles (and therefore by soil grading). As a consequence, in gassy soils different values of $k_{H,02}$ and $k_{H,N2}$ could be possible.

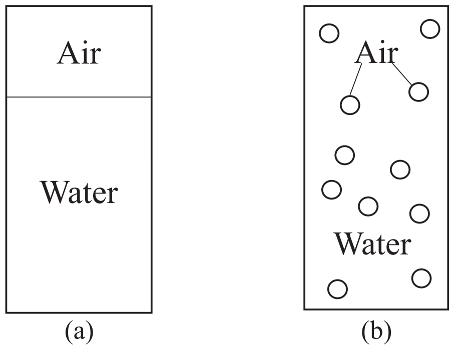



**Fig. 4**. Pore-fluid scheme: (a) continuous air and water phase; and (b) spherical bubbles into water [16].

### 3.1 Laboratory setup and testing programme

The laboratory device sketched in Figure 5 has been used to measure the volumetric strains of air/water mixture due to an increase of water pressure (induced through a piston pushed by pressurized air). The air/water mixture is placed in the upper camera of the cylinder. The volume change in upper camera can be measured knowing the vertical displacements of the piston.

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All tests have been performed by filling the upper camera with water and air in order to reach an initial degree of saturation of 95%. In order to investigate the effect of loading velocity and the "shape" of the air/water interface, different test procedures have been adopted.

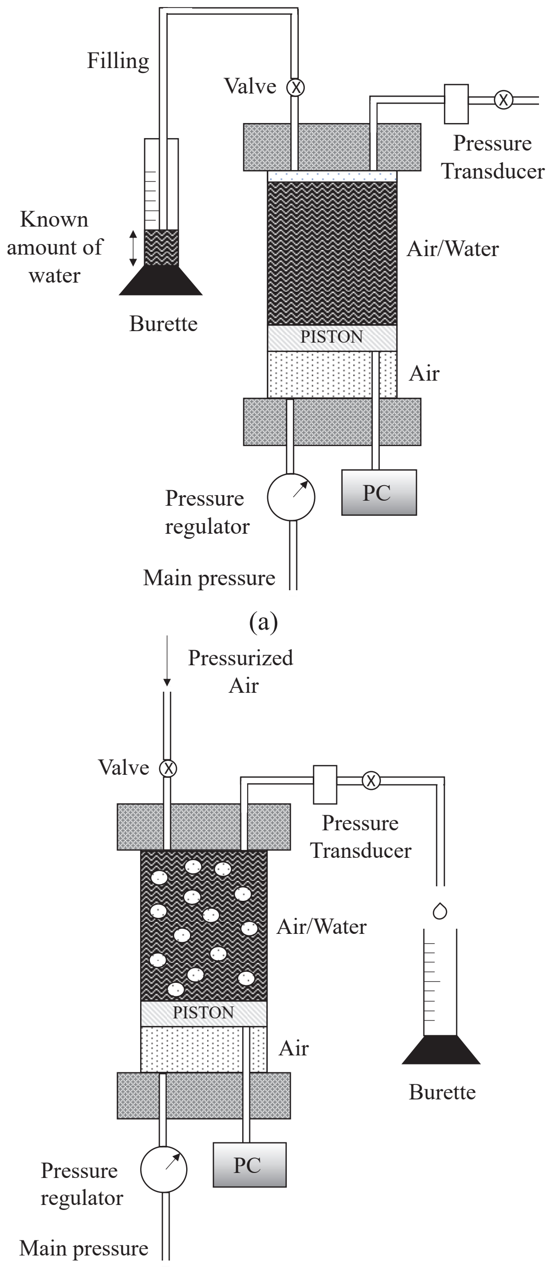



**Fig. 5**. Setup of the adopted device for two different testing procedures.

In the first two tests (Tab. 1) the upper camera has been filled with a known quantity of water and air, using a procedure that guarantees a sort of "planar" air/water interface. The procedure consists of pushing down the piston, pulling in a known amount of water and air through a burette (Fig. 5a).

In the last test (S_3s; Tab. 1), the upper camera has been first fully saturated. After that, pressurized air is injected from the upper filling tube generating many bubbles in the upper part of the camera. The amount of water going out has been collected from "pressure transducer pipe" (previously fully saturated) in order to quantify the injected air volume through a burette (Fig. 5b). In the tests, an external pressure of 50 kPa has been applied to the upper air/water mixture in a single step (S_1p) or with a constant loading rate of 10kPa/min (S_2p and S_3s). The resulting change in the air/mixture volume, measured by the piston displacements, represents the volumetric strains of the air phase (being more compressible than water).

**Table 1.** Testing programme.

| Test | Sr (%) | Shape of interface | Loading velocity (kPa/min) |
|---|---|---|---|
| S_1p | 95 | Plane | ∞ |
| S_2p | 95 | Plane | 10 |
| S_3s | 95 | Spherical | 10 |

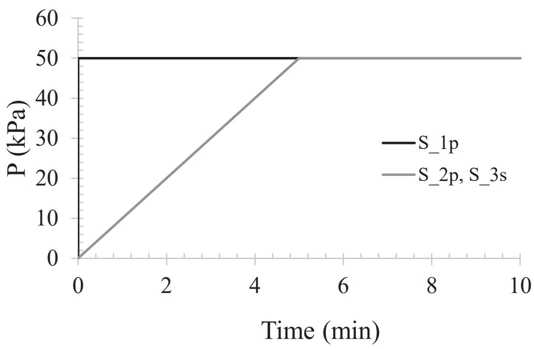



**Fig. 6**. Ramp pressure imposed in performed tests.

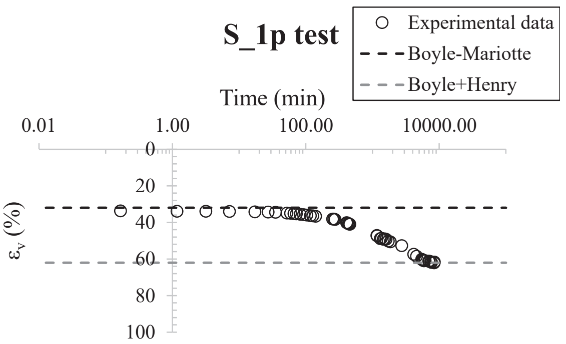
## 3.2 Results and considerations

The air volumetric strains $\varepsilon_v$, computed as the ratio between the measured volume change and the initial known air volume, have been plotted in Figure 7. In the same figure, the predicted volumetric strains induced by air compressibility (Boyle and Mariotte's law) and air solubility (Henry's law) has been reported as well.

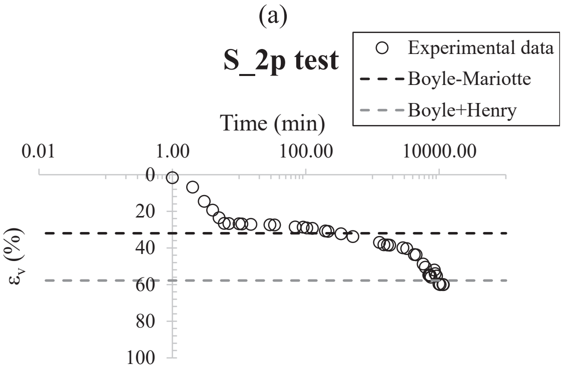
Looking at Figure 7a (S_1p test) it can be noted that a sudden decrease of air volume has been recorded due to the quick increase of water pressure. This component of $\varepsilon_v$ (32%) is mainly linked to the compression of air. For the following 50 minutes $\varepsilon_v$ is roughly constant, up to the triggering of the air dissolution phenomenon, responsible of the further volume change. The final experimental value of $\varepsilon_v$ (62%) matches the theoretical one, which stems from the sum of $\varepsilon_v$ due to air compressibility and air solubility into water (eq. 3).

In S_2p test (Fig. 7b) the effect of a slower load is evident. As expected, the air compression process takes more time than S_1p, reaching the theoretical values of $\varepsilon_v$ (32%) after 5 minutes, when the water pressure attains the imposed last value of 50 kPa. Also in this test the experimental data are in agreement with the theoretical predictions. Finally, in S_3s test (Fig. 7c) it can be noted that the volumetric strains induced by air compression are again in agreement with the theoretical value estimated by Boyle and Mariotte's law. On the contrary, the theoretical value due to dissolution (61%) underestimates the experimental measurements (80%). This result can be explained by the different “shape” of air/water interface that plays an important role in the dissolution process, ruled by Henry’s law. The high specific surface of the air bubbles, can be responsible of the higher volumetric strains compared to those theoretically estimated considering the simplified hypothesis of a planar air/water interfaces.

Regarding the time needed for the triggering of the dissolution process (ruled by eq. 2), it can be noted that in all tests the phenomenon starts very late (after 100 minutes). As reported by Fredlund [24], the diffusivity coefficient D of air into water can differ - also of one order of magnitude - from that measured in soils. It means that the dissolution process in a three-phase medium (gassy soils) can be significantly faster than that observed in tests performed on a two-phase medium (air/ water).




(a)

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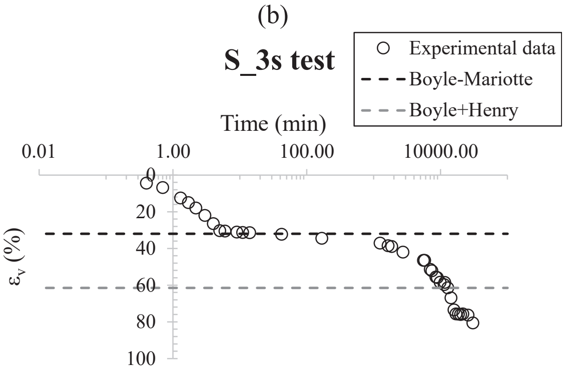


(c)

**Fig. 7**. Experimental results in terms of time – volumetric strains of air.

## 4 Concluding remarks

The study of the volumetric response of gassy soils ($S_r$ > 80%) highlighted that, at the laboratory scale, the low frequencies of applied cyclic loads can allow the development of the air dissolution phenomenon. The outcomes of simple tests performed on a two-phase medium confirm the hypothesis that air dissolution is increased by the high specific surface of the bubbles occluded into the fluid phase. This is the reason why the theoretical approaches that neglect such a dissolution phenomenon, cannot correctly quantify the potential volumetric strain measured in undrained cyclic tests on quasi-saturated soils.

At large scale, where air dissolution is probably inhibited by the features or a real seismic shaking (frequency and duration), the overall volumetric strain of a three-phases medium (gassy soils) is governed only by the air/gas bubble compressibility.

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