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STATE-OF-THE-ART REVIEW

Partial Saturation as a Liquefaction Countermeasure: A Review

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Abstract The liquefaction or softening of the soils and the potential vulnerability of existing buildings on liquefiable soils continue to be of major concern to the public because it has repeatedly caused severe damages to buildings during strong earthquakes, such as 1967 Niigata (Japan), 1999 Adapazari (Turkey), 2010 Maule (Chile), 2011 Christchurch (New Zealand) and 2011 Great East (Japan) earthquakes. Studies on liquefaction have been devoted to realizing the mechanism of liquefaction of fully saturated sands and developing liquefaction mitigation techniques during the last decades. In recent years, some researchers have discovered liquefaction mitigation procedures that are different from conventional techniques. They investigated techniques that involve a reduction in the degree of saturation and the creation of partially saturated zones in the liquefiable soil deposits. Since these techniques are relatively new and their efficiency and applicability to tackle the liquefaction in real projects is still being studied, the existence of a comprehensive literature review seems to be of interest for researchers to shed light on future studies. This literature review intends to present an abstract of the experimental and numerical studies on the liquefaction resistance of sands partially saturated as a liquefaction countermeasure. Also, noteworthy outcomes of the presented studies are presented here, chronologically ordered, in tables.

Keywords Partially saturated · Liquefaction resistance · Liquefaction mitigation · Degree of saturation · Desaturation

List of Symbols

S_r	Degree of saturation
K_{aw}	Air–water mixture bulk modulus
K'_{aw}	Modified Air–water mixture bulk modulus
C_{aw}	Air–water mixture compressibility
V_a	Volume of air
P_a	Atmospheric pressure
Δu	Excess pore pressure
N	Number of cycles
N_L	Number of cycles to reach liquefaction
$\Delta\sigma$	Change of applied confining stress
V_P	Velocity of compressional wave
$DA_{\varepsilon a} = 5\%$	5% Double amplitude axial strain
B-value	Skempton's coefficient
$\Delta\varepsilon_{vd}$	Change in voulmetric strain

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$\Delta\varepsilon_a$	Change in axial strain
C_u	Undrained shear strength
CSR	Cyclic stress ratio
LRR	Liquefaction resistance ratio
u	Pore water pressure
ε_a	Axial strain
a_{max} (g)	Maximum acceleration
D_r	Relative density
r_u	Excess pore pressure ratio
q	Deviatoric stress
u_0	Absolute pressure of fluid
σ'_v	Inintial effective stress
ε_v^*	Potential volumetric strain
$\varepsilon_{v\text{-shaking}}$	Volumetric strain during shaking
$\varepsilon_{v\text{-post}}$	Post shaking volumetric strain
γ	Shear strain
ε_v	Volumetric strain
S_{cyc}	Suction after cyclic shear
$\frac{\tau_m}{p'_c}$	Undrained shear stress ratio
r_{n5}	Stress reduction ratio observed at $DA\varepsilon_a = 5\%$
$\varepsilon_{v\text{-}5}$	Volumetric strain observed at $DA\varepsilon_a = 5\%$
S_{u5}	Matric suction observed at $DA\varepsilon_a = 5\%$
σ_{n0}	Initial net stress
$LRR_{DA=5\%}$	Liquefaction resistance ratio based on $DA_{\varepsilon a} = 5\%$
$\varepsilon^*_{v,air}$	Potential volumetric strain by pore air compression
ASR_{peak}	Peak average stress ratio
$r_{u,max}$	Maximum excess pore pressure ratio
Q	Foundation bearing pressure
N_{max}	Number of cycles to reach $r_{u,max}$
C_L	Additional cyclic strength at $DA\varepsilon_a = 5\%$
G_0	Small strain shear modulus
G_{max}	Maximum shear modulus
CRR	Cyclic resistance ratio
TFamp.	Transfer function amplitude
$E_{s,liq}$	Deviatoric specific energy to reach liquefaction.
γ_{max}	Maximum shear strain
$\frac{N_{PS}}{N_{FS}}$	Normalised number of cycles to reach liquefaction

1 Introduction

In recent years, some researchers have been investigating liquefaction mitigation techniques through a series of laboratory tests and numerical models that reduce the degree of saturation and partially saturated zones in the liquefiable soil deposits. These techniques are intended to prevent the occurrence of liquefaction by increasing the compressibility of the pore fluid with the generation of some amount of gas in the fully saturated sand pores, thus basically, by transforming the sand into a partially saturated state. Also, most of the natural geologic soils are not always saturated, and bubbles of undissolved gas have been found in soils at many locations in the world.

These gas bubbles can have a considerable effect on the soil's engineering properties because they can dramatically increase the compressibility of the pore fluid and increase the liquefaction resistance. Hence, there are many studies in the literature for investigating the influence of the degree of saturation on the liquefaction strength of soils through laboratory tests and numerical studies. Performance-based geotechnical earthquake engineering requires improved procedures to give a deep and more realistic insight into the field. Some researchers added chemical material to saturated soil to introduce gas bubbles and to increase the compressibility of the pore fluid (Yegian et al. 2007), while others tried to inject air into the saturated soil layer to make it partially saturated and liquefaction resistant (e.g., Marasini and Okamura 2015a). Dewatering would be another procedure to mitigate the liquefaction potential of a fully saturated sand layer (e.g., Yegian et al. 2007; Nakai et al. 2015).

Forming partially saturated zones in liquefiable soil deposits has been considered a liquefaction mitigation procedure. However, its efficiency in real-case applications is still being studied, so a comprehensive literature review in this field is of crucial need.

This literature review paper presents all the published studies performed on partially saturated sands and is divided into six main sections: first, studies on the misinterpretation of sands' liquefaction resistance due to imperfect saturation are presented. Next, experimental and analytical studies on partially saturated sands are given. Then, partial saturation techniques developed for liquefaction mitigation in the literature are summarized. Subsequently, experimental and numerical studies on the liquefaction resistance of sands partially saturated as a liquefaction countermeasure and studies on the sustainability of partial saturation in sands are discussed. Finally, research gaps in the literature are discussed, and suggestions for future research are stated. Each section summarizes key points and noteworthy outcomes of studies on the liquefaction analysis of imperfectly saturated sands and presents state-of-the-art approaches in the field. This paper aims to make researchers familiar with current thinking and research in this field and justify future research into this previously understudied area.

2 Studies on the Misinterpretation of Liquefaction Resistance of Sands due to Imperfect Saturation

The problem of the poor performance of fully saturated loose sands under the cyclic loading during earthquakes has been one of the main reasons of concern among geotechnical engineers in seismically active areas. In the presence of these gas bubbles, sandy soils can be considered as partially saturated because the degree of saturation, S_r, of saturated sand drops and becomes less than 100%. It is noticeable that in experimental studies, the B-value defined as the ratio of the induced excess pore water pressure to the applied confining stress ($\Delta u/\Delta\sigma$) is used instead of S_r as an indicator of saturation level of soils. To distinguish between fully and imperfectly saturated sands and also to determine the degree of saturation of sand samples, practical engineers usually use techniques to quantify the propagating velocity of the compressional wave, V_P, (e.g., Ishihara et al. 2001).

According to the literature findings, imperfectly saturated sands have higher undrained strength and are less prone to liquefaction under cyclic loadings. Also, experimental studies have shown that reducing the degree of saturation can significantly decrease V_P (e.g., Sherif et al. 1977; Chaney 1978; Wheeler 1988; Xia and Hu 1991; Fourie et al. 2001; Ishihara et al. 2001, 2004; Tsukamoto et al. 2002; Yang 2002; Pietruszczak et al. 2003; Ishihara and Tsukamoto 2004). Figure 1 represents test results in which the cyclic stress ratio is plotted against the number of cycles, N, to reach a double amplitude of shear strain (DA) of 5%. It is seen in this figure that by decreasing the degree of saturation or B-value, the liquefaction resistance is increased.

Yang et al. (2004) used laboratory test data and suggested an empirical correlation between the liquefaction strength and B-value for evaluating the saturation effects on sand's liquefaction strength. The liquefaction strength in the correlation was defined as the cyclic stress ratio required to reach liquefaction at 20 cycles.

Figure 2 shows the normalized liquefaction strength versus V_P for Toyoura sand. Despite the attainment of valuable results from studies during the last decades (mainly before 2006), the researchers conducted their studies to demonstrate misinterpretations of fully saturated sands' liquefaction resistance due to partial saturation in the test samples. Most of these studies confirmed that when a fully saturated sand sample is prepared with air entrapped in it, more numbers of cycles are required to reach liquefaction.

Also, partial saturation can increase the cyclic undrained strength of saturated sand specimens. Likewise, some experimental studies have shown that even if the soil is partially saturated, it can reach a zero effective stress state under certain conditions and liquefy (Sherif et al. 1977; Ishihara and Tsukamoto 2004; Unno et al. 2008; Vernay et al. 2016).

The experimental studies demonstrating the misinterpretation of fully saturated sands' liquefaction resistance due to air entrapment in the sample led other researchers to profoundly investigate the resistance of partially saturated sands to liquefaction. Some of them considered partial saturation as a potential mitigation technique for liquefiable soils.

3 Studies on Partially Saturated Sands

3.1 Experimental Studies

To evaluate the liquefaction resistance of partially saturated sands under monotonic and cyclic loadings, some laboratory tests were conducted on sand samples using different types of test apparatuses. Primarily, this section provides a review of some of these studies and key findings.

3.1.1 Experimental Studies Using the Triaxial Test Setup

One of the most extensively executed tests in geotechnical laboratories is the cyclic triaxial test.

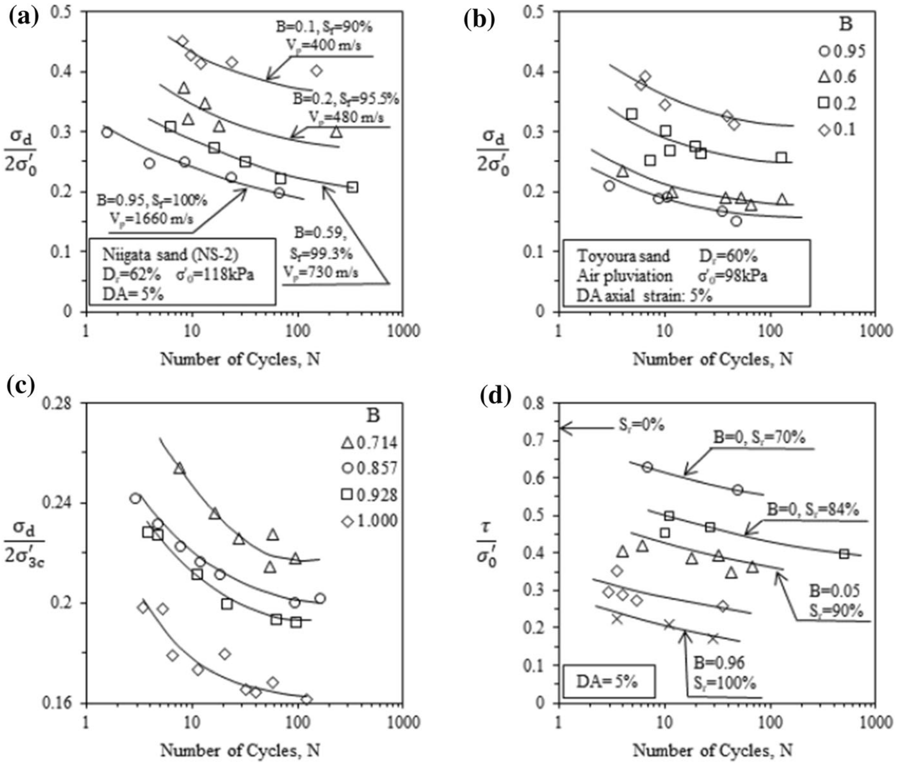

Fig. 1 Effects of the degree of saturation (or B-value) on liquefaction resistance of the sand data from **a** Ishihara et al. (2001), **b** Ishihara and Tsukamoto (2004), **c** Xia and Hu (1991), **d** Yoshimi et al. (1989)

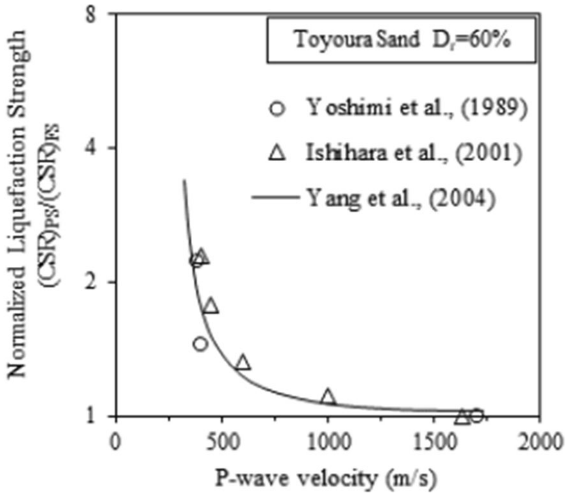

Fig. 2 Normalized liquefaction strength as a function of P-wave velocity for Toyoura sand

The benefit of triaxial tests is that pore pressure is measured by controlling the specimen drainage; other tests use different geotechnical laboratory methods to define shear strength. The triaxial test determines parameters such as the internal angle of friction (φ), cohesion (c), shear strength, and V_P as a means to identify S_r or the B-value of soil samples. A vertical impact is applied at the top, and by monitoring its arrival at the bottom of the specimen, V_P is generated and measured. During the last decades, cyclic triaxial tests have been conducted to evaluate the effect of S_r on liquefaction resistance of partially saturated sand specimens.

Sawada et al. (2006) performed a series of triaxial tests to observe the volume changes of imperfectly saturated soil specimens during shaking in an undrained condition and during post-shaking in a drained condition. Their experiments revealed that most of the volume changes occur in partially saturated sands during the undrained phase of shaking because of the air compressibility. The volume change during post-liquefaction drainage was smaller for partially saturated specimens due to less pore pressure buildup during the undrained phase. Finally, it was concluded that total volumetric strain is higher in partially saturated sands under applied shear strains less than 10%.

Kamata et al. (2009) conducted a series of isotropically consolidated undrained triaxial compression and extension tests on Toyoura sand to examine the undrained shear strength of partially saturated sands considering the steady-state concept. They showed that under triaxial tests, the undrained shear strength of sands decreases by increasing S_r. According to the test results obtained from the triaxial test apparatus, it can be concluded that any reduction in S_r (or B-value) causes a decrement in V_P. Moreover, it was shown that reducing S_r or the B-value can significantly increase the liquefaction resistance defined as the cyclic stress ratio $(\sigma_d/(2\sigma'_0))$ (Hatanaka and Masuda 2009; Arab et al. 2011, 2015; Tsukamoto et al. 2014; Wang et al. 2016; Świdziński et al. 2017; Fioravante et al. 2019; Tsukamoto 2019). Figure 3 presents the cyclic stress ratio versus the number of cycles required to cause a 5% double amplitude of axial strain ($DA_{\varepsilon_a} = 5\%$). It is noted that the black data points shown in this figure did not reach up to $DA_{\varepsilon a}$ of 5%. According to Fig. 3, the liquefaction resistance of sands increases by decreasing the B-value (or degree of saturation). Experimantal tests on partially saturated small samples showed that the development of excess pore pressure and axial strains was slower and the liquefaction condition occurred after higher values of number of cycles. Although the occurrence of liquefaction in partially saturated sands was observed in some small-scale experimental tests in the literature, but this is against the hypothesis of the present paper. It is anticipated that the liquefaction does not occur in partially saturated sands even by increasing the number of cyclic loadings. The reason of liquefaction occurrence in partially saturated small samples could be due to the limitations of these tests (like the escape of the entrapped air from samples) which will be discussed later in this paper.

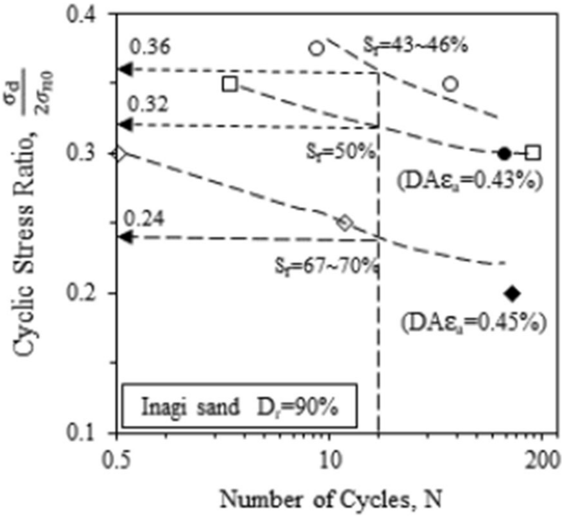

Fig. 3 Cyclic stress ratio versus number of cycles (Data from Tsukamoto 2019)

Apart from the effect of partial saturation on the liquefaction resistance of partially saturated sands that were discussed above, some experimental studies have been done to assess the dynamic properties like shear modulus and damping ratios. Chakrabortty et al. (2020) conducted some strain-controlled cyclic triaxial tests to estimate the dynamic properties and the cyclic behavior of synthetic fine and medium-size grained sands partially saturated.

They tested some natural sand samples with different B-values (or S_r) to use in the triaxial setup. The experimental results demonstrated that the shear modulus and damping ratio reduce with the increase in S_r due to the decrease in the pore fluid's compressibility containing air bubbles. Also, it was shown that in partially saturated sands, r_u generation decreases with the reduction in S_r due to the higher compressibility of the pore fluid in the presence of the air bubbles.

3.1.2 *Experimental Studies Using the Torsional Simple Shear Test Setup*

Okur and Umu (2013) conducted resonant column and dynamic torsional shear tests under undrained conditions to evaluate the effects of factors such as the amplitude of shear strain, relative density, saturation ratio, and confining pressure on the dynamic characteristics of the partially saturated sand and energy dissipation. They used the energy concept for the evaluation of the cyclic behavior of partially saturated sands. They concluded that the magnitude of confining stress has a considerable influence on partially saturated sands' dynamic behavior. Furthermore, the unit energy required for the same deformation in partially saturated sands is 3–4 times greater than for saturated sands. On the other hand, partially saturated sand needs higher energy to fail than fully saturated sand.

3.1.3 *Experimental Studies Using the Centrifuge Test Setup*

Intricate problems such as earthquake-induced liquefaction or soil-structure interaction can be modeled and solved by a centrifuge test setup thanks to its reliable test results, time, and cost-effectiveness. Centrifuge model testing delivers data to enhance our understanding of the basic mechanisms of deformation and failure and provides indices useful for validating numerical models. Some researchers have used centrifuge testing to evaluate the effect of partial saturation in increasing the liquefaction resistance of fully saturated sands in free-field conditions and also under foundation pressure.

Centrifuge tests of partially saturated sand specimens conducted by Byrne et al. (2004) confirmed that the excess pore pressure rise in the fully saturated sample was significantly faster than that observed in the partially saturated one under the same applied load. Raghunandan and Juneja (2011) conducted a centrifuge test to study the effect of desaturation on the cyclic response and liquefaction resistance of sands. They used an air intrusion technique in the sand to desaturate samples. They observed that the reduction in the degree of saturation increases the number of cycles required for liquefaction by 1.5–2.5 times that of fully saturated sand.

Ghayoomi et al. (2013) conducted a series of dynamic centrifuge tests on two pile-supported models to investigate the effects of soil's degree of saturation on the seismic behavior of pile-supported superstructures. They implemented a steady-state infiltration system to control the degree of saturation in the sand profile prior to shaking. For the tests conducted on systems with piles embedded in partially saturated sand, acceleration amplification of superstructure was higher than that of the dry sand tests. Also, partial saturation lowered the lateral deformation of pile-supported superstructures. This was due to the higher stiffness of partially saturated sand, which caused lower shear strains in the soil layer and restricted lateral deformations.

Mirshekari and Ghayoomi (2017a, b) prepared partially saturated sand samples using a steady-state infiltration technique to conduct centrifuge seismic models to assess the seismic site response of partially saturated sands. The seismic modeling results were shown in terms of normalized acceleration, settlement, arias intensity time histories, Peak Ground Acceleration (PGA) amplification factor, and FFT amplitude of the motions for one dry and two partially saturated specimens. According to the results, the surface-to-base PGA amplification factor was found to be higher for partially saturated conditions, especially for the test with a lower degree of saturation. Also, more energy was accumulated within the sand layers during the earthquake in partially saturated tests. Furthermore, a lower seismic settlement was observed for the partially saturated sandsspecific energy spent to reach due to their increased stiffness.

3.1.4 *Experimental Studies Using* $1-g$ *Shaking Table Test Setup*

If the test's purpose is to confirm the numerical model or comprehend the primary failure mechanisms, shaking table tests can be executed in geotechnical engineering. This test setup has the benefit of being a well-controlled, large amplitude, multi-axis input motion application. Zhang et al. (2019) conducted shaking table tests and used a horizontal-vertical shaker to characterize the seismic behavior of partially saturated sands. They showed that the liquefaction resistance of partially saturated sand increases due to the decrement of the degree of saturation at similar initial effective vertical stresses. Also, partially saturated sand liquefaction resistance increases with an increase of the initial effective stress at a similar degree of saturation. In addition, as for a specific sandy soil, the margin between the liquefied and non-liquefied sand becomes wider and wider during shaking, which can hardly be simulated in element tests.

3.2 Analytical Studies

In the past few decades, the experimental analysis of the liquefaction response of partially saturated sands under monotonic and cyclic loadings has been conducted by many researchers. Although there are many noteworthy outcomes from experimental analyses, these studies face some limitations (i.e., expensive test apparatus, sample preparation difficulty, effective stress levels, etc.). Therefore, some researchers have been turning to numerical analyses of the liquefaction response of sands. They develop constitutive numerical models to simulate soils' undrained behavior under loadings and try to validate experimental studies with these numerical models (e.g., Jafari-Mehrabadi 2007).

Based on soil mechanics theory, partially saturated soil is composed of three phases: soil skeleton, water, and air. Considering this concept, Pietruszczak et al. (2003) obtained the mechanical properties of partially saturated sands from their triaxial tests and employed them in a mathematical simulation. They used a deviatoric hardening model to simulate the soil behavior. The partial saturation state was considered by lowering the degree of saturation to define an appropriate B-value. They compared the numerical results with those obtained from triaxial tests and observed good similarities. It was shown that the saturated sample liquefies after a few cycles, but the partially saturated sample requires a higher number of cycles to liquefy.

The mechanism of modeling the behavior of partially saturated sands subjected to external loadings is similar to that of a fully saturated one. The only parameter that makes a difference between the fully and partially saturated cases is the compressibility of pore fluid, because of the presence of air bubbles. Some mathematical equations have been introduced for air–water mixture compressibility (e.g., Fredlund 1976); these equations are used in numerical modelings of partially saturated soils. One of the most commonly used equations is the one which was introduced by Koning (1963) as expressed in Eq. (1):

$$C_{aw} = \frac{1}{K_{aw}} = \frac{S_r}{K_w} + \frac{1 - S_r}{K_a} \tag{1}$$

where C_{aw} is air–water mixture compressibility, K_{aw} is air–water mixture bulk modulus, S_r is the degree of saturation, K_w is the bulk modulus of water, and K_a is the bulk modulus of air.

Since a relation between B and the P-wave velocity has been defined before by some researchers (e.g., Ishihara et al. 2001), another correlation between the liquefaction strength of sand and its V_P, was proposed by Yang et al. (2004). According to their proposed correlation, normalized liquefaction strength (cyclic stress ratio of partially saturated sand to that of fully saturated) was increased while P-wave velocity decreased as previously demonstrated in Fig. 2).

The water in the pores of fully saturated sands acts as a volumetric constraint on the skeleton. Under cyclic loadings and in undrained conditions, this constraint causes a pore pressure build-up instead of volumetric strain in the soil. However, while in partially saturated sands, in the presence of air–water mixture, the constraint is somehow dampened, and the developed volumetric strain reduces the level of pore pressure generation. Calculating the air–water mixture's stiffness, Seid-Karbasi and Byrne (2006) used a coupled stress-flow dynamic analysis procedure to perform an investigation on partial saturation effects on liquefiable ground response. They concluded that a partial saturation condition in a uniform liquefiable soil profile results in lower excess pore pressures and lateral surface displacements. It also lowers the rate of pore pressure dissipation. Finally, they showed that partial saturation can result in an increase or decrease of displacements due to excess pore pressure redistribution conditions for a soil profile with a low permeability layer.

To assess the influences of the soil saturation on the behavior of partially saturated soils subjected to cyclic loading in undrained conditions, Bian and Shahrour (2009) and Bian et al. (2009) performed an analytical study. They took into account the multiphase theory of Coussy (2004) to write a state equation for partially saturated sandy soils. This state equation includes two parameters that should be defined in analytical studies: Biot modulus, M, and Biot coefficient, b. For sandy soils, coefficient b is equal to 1.0 because the soil grains are incompressible. Bian and Shahrour (2009) and Bian et al. (2009) showed that the biot modulus could be calculated as follows:

$$\frac{1}{M} = \frac{nS_r}{K_w} + \frac{n(1 - S_r)}{K_a} \tag{2}$$

where n is porosity. They employed these concepts in an elastoplastic constitutive model called "MODSOL" to simulate partially saturated sands' undrained behavior under monotonic and cyclic loadings. MODSOL model utilizes two loading surfaces: the first one describes the soil behavior under monotonic loading, and the second one recounts the soil behavior under cyclic loading.

Bian and Shahrour (2009) and Bian et al. (2009) performed a numerical study to assess the effect of entrapped gas on the liquefaction resistance of partially saturated sands, with an emphasis on the bulk modulus of the gas–water mixture. They showed that by increasing the gas content (decreasing the degree of saturation in the soil), the water–gas mixture's bulk modulus decreases, consequently, the pore pressure generation rate decreases, which means a reduction in the liquefaction risk. Later on, Bian et al. (2017) used the same model and code to examine the effect of the water table's position on the liquefaction behavior of a partially saturated soil layer subjected to cyclic loading. They confirmed that by decreasing the degree of saturation or lowering the water table in the soil, the extension of soil liquefaction is reduced.

Ghayoomi et al. (2010) showed that the equivalent linear approaches are unable to calculate the settlement of partially saturated sand under earthquake loading and that they should be improved. Hence, they synthesized procedures from the literature to introduce a quasi-effective, stress-based methodology for predicting the settlement of imperfectly saturated sand layers during earthquake excitation. An effective stress-based empirical methodology was proposed to predict the seismically induced settlement of a free-field layer of partially saturated sand (Ghayoomi et al. 2013). Also, the excess pore pressure ratio of partially saturated sand was related to that of saturated sand through a power function involving the degree of saturation, as stated in Eq. (3):

$$r_u = r_{u-sat} S_r^{3.5} \tag{3}$$

where $r_{u\text{-sat}}$ is a pore pressure ratio in a water-saturated soil specimen. It is concluded from Eq. (2) that r_u in partially saturated sand is lower than that of fully saturated sand. So, partial saturation can reduce pore pressure generation and prevent liquefaction.

Ghayoomi and McCartney (2016) proposed an empirical procedure based on available test data from the literature to estimate the seismic settlement of partially saturated sands. This procedure takes into account the effect of the degree of saturation. The results indicate that seismic settlements of sands with intermediate degrees of saturation ($40\% < S_r < 60\%$) will be lower than the settlements in dry or nearly saturated sands (see Fig. 4).

As discussed in Sect. 3.1.1, Chakrabortty et al. (2020) used a triaxial test setup to evaluate the dynamic properties of partially saturated sands. They interpreted the results and found out that the liquefaction resistance of partially saturated sands depends on the soil type and the developed r_u. Finally, they proposed a mathematical expression to calculate the strength against liquefaction in terms of the developed peak average stress ratio as stated below:

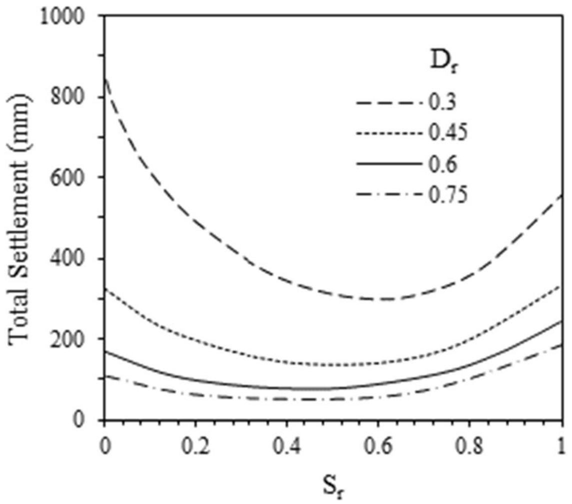

Fig. 4 Effect of degree of saturation on predicted settlements of a sand layer with different relative densities, D_r, (data from Ghayoomi and McCartney 2016)

$$ASR_{peak} = \frac{\left(\frac{\sigma_{d\max Comp}}{2\sigma_3'}\right) + \left(\frac{\sigma_{d\max Ext}}{2\sigma_3'}\right)}{2} \tag{4}$$

where the first parenthesis shows the maximum stress ratio obtained from the strain-controlled cyclic triaxial test under compression, and the second one presents the extension loading condition. Due to the compressibility of air/gas bubbles, less development in r_u is observed in partially saturated sands in comparison with the fully saturated ones. Hence, it can be concluded that the partial saturation can increase ASR_{peak} (developed peak average stress ratio) and the liquefaction resistance of the soils, consequently. Figure 5 illustrates the variation of ASR_{peak} with the developed $r_{u,max}$ at various S_r (or B-values) in dense and loose medium sands. It shows that the developed peak average stress ratio (or strength against liquefaction) is dropped by increasing $r_{u,max}$. Furthermore, it confirms that the partial saturation can significantly increase the ASR_{peak}, so the liquefaction resistance of sands.

Vucetic and Dobry (1986) introduced a model to predict r_u responses of sands at any number of cycles (*N*) of shear strains as stated below:

$$\frac{1}{r_u} = \frac{1}{p} + \frac{1}{p \times F \times f \times N \times (\gamma - \gamma_{tvp})^s} \tag{5}$$

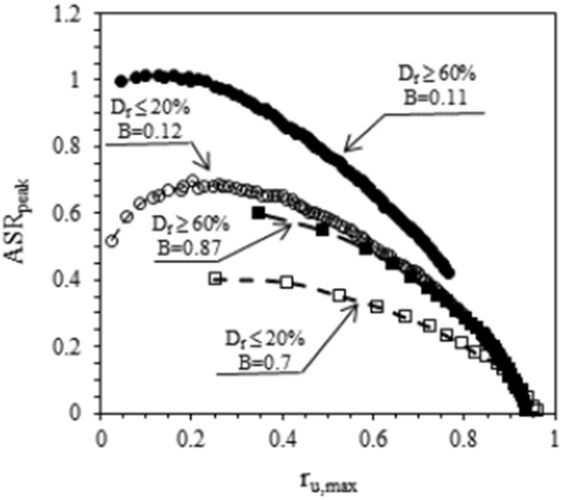

Fig. 5 $\mathrm{ASR_{peak}}$ versus $\mathrm{r_{u,\,max}}$ in dense and loose medium sands at various B-values (data from Chakrabortty et al. 2020)

where *p*, *F*, and *s* are the model fitting parameters and depend on volumetric deformation of soils and are defined by laboratory data-based fitting trials. *f* can be 1 or 2 depending on whether pore pressure is induced by one or two-directional loading, *p* is very close to 1, γ is cyclic shear strain amplitude, and γ_{tvp} is threshold cyclic shear strain amplitude. It will be later shown in the present paper that parameter *F* is reversely proportional to the shear wave velocity of the soil, $\mathrm{V_s}$.

Parallel to the determination of dynamic properties of sands by triaxial tests, Chakrabortty et al. (2020) modified a mathematical model available in the literature to predict excess pore pressure ratio. Chakrabortty et al. (2020) used the triaxial test results and modified Eq. (5) to predict $\mathrm{r_u}$ in partially saturated sands as:

$$\frac{1}{r_u} = a\frac{1}{N} + b \tag{6}$$

where *b* is almost equal to 1 and *a* is dependent on B-value (or $\mathrm{S_r}$). Finally, it was shown that the parameter *F* is dependent on B-value (or $\mathrm{S_r}$), $\mathrm{D_r}$ and grain size of the soil.

Since some of these numerical studies are based on limited data and hypotheses, additional research is needed to refine some of the empirical relationships and improve the procedure's overall accuracy for predictive purposes. As a summary, key findings reported in the literature from studies on the liquefaction resistance of sands due to partial saturation are tabulated in Table 1.

4 Partial Saturation Techniques Developed for Liquefaction Mitigation in the Literature

As discussed earlier, the liquefaction resistance of sands due to partial saturation had been extensively studied by researchers over the years. Even in partially saturated sands, the main aim of many researchers was liquefaction occurrence, and $\mathrm{r_u} = 1$ was the control parameter of liquefaction triggering. Consequently, thanks to the increment of the number of cycles required to reach liquefaction and also the increment of undrained shear strength of partially saturated sands, it had been concluded that partial saturation is an effective way to increase the liquefaction resistance of saturated sands. Subsequent contributions focused on the reduction in the liquefaction potential of soils as a result of the presence of small amounts of gas bubbles and became an inspiration for researchers to develop a novel liquefaction countermeasure.

Okamura and Teraoka (2006) proposed a cost-effective liquefaction mitigation technique by inserting a pipe into liquefiable soils and exhausting air from the tip to desaturate the soil. They showed that excess pore pressure generation generated less in voids and consequently increased the soil's liquefaction resistance.

Yegian et al. (2007) proposed Induced Partial Saturation (IPS) to mitigate the liquefaction hazards of sands. They designed a special Cyclic Simple Shear Liquefaction Box (CSSLB) to investigate the feasibility of IPS as a liquefaction mitigation technique. They prepared partially saturated specimens by the wet pluviation of powdered sodium perborate monohydrate mixed with Ottawa sand. Then, a series of cyclic shear strain-controlled tests was done on fully and partially saturated sands.

Later on, He et al. (2013) developed a biogas method and used denitrifying bacteria to generate miniature nitrogen gas bubbles in the sand. Pore water pressure generated in the sand partially saturated by this method was much smaller than that in saturated sand.

All three methodologies of inducing partial saturation mentioned above have inspired other researchers to extend and employ these techniques in their studies.

Table 1 Overview of key findings reported in the literature from studies on the liquefaction resistance of sands due to partial saturation

References	Analysis type		Partial saturation preparation method	Parameters to be studied	Outcomes and concluding remarks
	Experimental	Numerical			
Koning (1963)	–	An empirical equation for air–water mixture bulk modulus	By using Boyle's law	S_r, K_{aw}	$S_r\downarrow$: $K_{aw}\downarrow$
Fredlund (1976)	–	Introducing a formula for C_{aw} using Boyle's Law and Henry's Law	Using C_{aw} for air–water mixture compressibility	V_a, C_{aw}	$V_a\uparrow$: $C_{aw}\uparrow$
Sherif et al. (1977)	Torsional simple shear test	–	By adjusting the backpressure level during the test	S_r (B-value), Δu, N_L, N	For a given N_L, S_r (B-value) $\downarrow$: CSR$\uparrow$ For a given N, S_r (B-value)$\downarrow$: $\Delta u\downarrow$
Chaney (1978)	Triaxial test	–	By adjusting the backpressure level during the test	S_r, N_L, Δu, B-value, K_{aw}, $\Delta\varepsilon_{vd}$, $DA_{\varepsilon a}$	B-value$\downarrow$: $N_L\uparrow$ $S_r\downarrow$: $K_{aw}\downarrow$ For a given S_r, $\Delta u\uparrow$: $\Delta\varepsilon_{vd}\uparrow$ For a given N, B-value$\uparrow$: $DA_{\varepsilon a}\uparrow$
Wheeler (1988)	Triaxial test	–	Reconstituted soil samples containing gas bubbles	S_r, C_u, Consolidation pressure, Backpressure	$S_r\downarrow$: C_u can be either increased or decreased depending on consolidation pressure and backpressure
Yoshimi et al. (1989)	Cyclic torsional shear test	–	By CO_2 gas	S_r, N_L, CSR, B-value, LRR	S_r (or B-value) $\downarrow$: LRR$\uparrow$ S_r (or B-value) $\downarrow$: $N_L\uparrow$ S_r (or B-value)$\downarrow$: CSR$\uparrow$
Xia and Hu (1991)	Triaxial test	–	By adjusting the backpressure level during the test	S_r, B-value, LRR, Backpressure	B-value$\downarrow$: LRR$\uparrow$ $S_r\downarrow$: LRR$\uparrow$ Backpressure$\uparrow$: LRR$\uparrow$
Fourie et al. (2001)	Triaxial test	–	Extraction of undisturbed samples of tailings sand, which contains occluded air	S_r, B-value, Δu	$S_r\uparrow$: $\Delta u\uparrow$ $S_r\uparrow$: B-value$\uparrow$ $S_r\downarrow$: Liquefaction potential$\downarrow$
Ishihara et al. (2001)	Triaxial test	–	By adjusting the backpressure level during the test	B-value, V_p, CSR, N, r_u, N_L, D_r	For a given N, S_r (or B-value) $\downarrow$: CSR$\uparrow$ S_r (or B-value) $\downarrow$: $N_L\uparrow$ S_r (or B-value) $\downarrow$: $V_p\downarrow$ $V_p\downarrow$: CSR$\uparrow$ For a given B-value, $D_r\downarrow$: CSR$\downarrow$

Table 1 continiued

References	Analysis type		Partial saturation preparation method	Parameters to be studied	Outcomes and concluding remarks
	Experimental	Numerical			
Tsukamoto et al. (2002)	Triaxial test	–	By controlling the B-value during the test, the degree of saturation was defined	B-value, CSR, N, V_p, D_r	B-value ↓: V_p ↓ For a given N, B-value ↑: CSR↑ For a given D_r, V_p↑: CSR↓ For a given D_r, B-value↓: CSR↑
Yang (2002)	–	Development of an empirical function to relate the liquefaction resistance to the B-value	Laboratory test data in the literature were used	B-value, CSR, V_p,	B-value↓: V_p↓ B-value↓: $\frac{N_{PS}}{N_{FS}}$↑
Pietruszczaket al. (2003)	Triaxial test	Simulation of triaxial tests using a constitutive model	De-aired water mixed with sand	ε_a, u, S_r	For a given ε_a, S_r↓: u↓ S_r↓: Liquefaction potential↓
Byrne et al. (2004)	Centrifuge test	Fully coupled effective stress model “UBCSAND”	Using carbon dioxide gas	S_r, Δu, a_{max} (g)	S_r↓: Rate of Δu generation↓ For a given depth, S_r↓: a_{max} (g)↑
Ishihara and Tsukamoto (2004) and Ishihara et al. (2004)	Triaxial test	–	By adjusting the backpressure level during the test	B-value, V_p, CSR, N, r_u, q, ε_a, N_L, D_r	For a given N, S_r (or B-value) ↓: CSR↑ S_r (or B-value) ↓: N_L↑ S_r (or B-value) ↓: V_p↓ V_p↓: CSR↑ For a given B-value, D_r↓: CSR↓ For a given q, B-value↓: ε_a ↑
Yang et al. (2004)	–	Developing an empirical correlation between the liquefaction strength and the B-value	Using a theoretical relation between V_P and the B-value	V_P, B-value, CSR	B-value↓: CSR↑ V_P↓: CSR↑ B-value↓: V_P↓
Okamura and Soga (2006)	Triaxial test	–	By adjusting the backpressure level during the test	S_r, σ'_v, ε_v^*, N, CSR, u_0, LRR	For a given N, S_r↓: CSR↑ For a given S_r, σ'_v↓: CSR↓ For a given S_r and u_0, σ'_v↑: CSR↑ 4. ε_v^*↑: LRR↑
Sawada et al. (2006)	Triaxial test	–	By the wet tamping method	ε_a, $\varepsilon_{v\text{-shaking}}$, $\varepsilon_{v\text{-post}}$, S_r, r_u, ε_v, γ	S_r↓: r_u↓ S_r↓: ε_a ↓ S_r↓: $\varepsilon_{v\text{-shaking}}$ ↑ S_r↓: $\varepsilon_{v\text{-post}}$ ↓ For $\gamma < 10\%$, S_r↓: ε_v ↓
Seid-Karbasi and Byrne (2006)	–	Using the “UBCSAND” Constitutive Model for Sand	By calculating the B-value for partially saturated sands	S_r, r_u, Lateral disp.	S_r↓: r_u↓ S_r↓: Lateral disp.↓

Table 1 continiued

References	Analysis type		Partial saturation preparation method	Parameters to be studied	Outcomes and concluding remarks
	Experimental	Numerical			
Jafari-Mehrabadi et al. (2007)	–	A multi-yield plasticity soil constitutive model	Using K_{aw} for partially saturated sand proposed in Koning (1963)	CSR, N, r_u, B-value	For a given N, B-value↓: CSR↑ For a given N, B-value↓: r_u↓
Unno et al. (2008)	Triaxial test	–	By controlling the drainage and suction in the samples	Effective stress reduction ratio, S_r, S_{cyc}	S_r↓: S_{cyc}↑ S_r↓: Effective stress reduction ratio↓ Even if the soil is unsaturated, the soil reaches a zero effective stress state under certain conditions
Bian et al. (2009)	–	Cyclic elastoplastic constitutive model “MODSOL”	By adjusting the porosity of the soil and the compressibility of pore fluid, introduced in Koning (1963)	S_r, Δu, K_{aw}, Settlement	S_r↓: Rate of Δu generation↓ S_r↓: K_{aw}↓ S_r↓: Liquefaction potential↓ S_r↓: Settlement↑ because of the compressibility of air bubbles
Kamata et al. (2009)	Triaxial test	–	By adjusting the backpressure level during the test	Δu, B-value, q, $\frac{\tau_m}{p'_c}$	B-value↓: Δu↓ B-value↓: q↓ In triaxial compression, B-value↓: $\frac{\tau_m}{p'_c}$↓ In triaxial tension, B-value↓: $\frac{\tau_m}{p'_c}$↑
Ghayoomi et al. (2010)	–	Development of a quasi-effective, stress-based methodology for predicting the settlement of partially saturated sand during shaking	By adjusting capillary forces and matric suction in the code	S_r, r_u, a_{max} (g), D_r, Settlement	S_r↓: Settlement↓ S_r↓: r_u↓ 3. For a given depth, S_r↓: a_{max} (g)↑ 4. For a given S_r, D_r↓: Settlement↑
Arab et al. (2011)	Triaxial test	–	Carbon dioxide passage and percolation with de-aired water	B-value, N_L, Δu, CSR, ε_a, q	B-value↓: N_L↑ B-value↓: CSR↑ For a given CSR, B-value↓: Δu↓ For given deviatoric stress, B-value↓: ε_a ↓
Raghunand and Juneja (2011)	Centrifuge test	–	Desaturation using the air intrusion technique	G_{max}, γ, N_L, S_r, LRR, r_u	S_r↓: N_L↑ S_r↓: r_u↓ S_r↓: LRR↑ For a given γ, S_r↓: N_L↑ For a given γ, S_r↓: G_{max}↑

Table 1 continiued

References	Analysis type		Partial saturation preparation method	Parameters to be studied	Outcomes and concluding remarks
	Experimental	Numerical			
Okur and Umu (2013)	Resonant column and dynamic torsional shear tests	–	By the moist tamping method	CSR, γ, S_r, Dissipated energy, N, D_r,	For a given N and γ, Sr↓: CSR↑ For a given N and D_r, S_r↓: Dissipated energy↓ For a given γ and D_r, S_r↓: Dissipated energy↑ $S_r < 60\%$: No cyclic shear because of matric suction
Tsukamoto et al. (2014)	Triaxial test	–	Retrieved partially saturated sand samples	r_{n5}, S_r, ε_{v5}, CSR,$\frac{S_{us}}{\sigma_{no}}$	S_r↓: r_{n5}↑ S_r↓: CSR↑ S_r↓: ε_{v5} ↓ S_r↓: $\frac{S_{us}}{\sigma_{no}}$↑
Arab et al. (2015)	Triaxial test	A mathematical relation to correlating LRR with the B-value	Soil sample was swept by CO_2, and then deaerated water was circulated inside the sand sample	B-value, CSR, ε_a, LRR, Pore Pressure, q, S_r, N	For a given q, B-value↓: ε_a ↓ For a given ε_a, B-value↓: Pore Pressure↓ S_r↓: LRR↑ For a given CSR, B-value↓: ε_a ↓ For a given N, B-value↓: CSR↑
Ghayoomi and McCartney (2016)	–	Development of a quasi-effective, stress-based methodology for predicting the settlement of partially saturated sand during shaking	By adjusting capillary forces and matric suction in the code	S_r, r_u, a_{max} (g), D_r, Settlement	S_r↓: Settlement↓ S_r↓: r_u↓ For a given depth, S_r↓: a_{max} (g)↑ For a given S_r, D_r↓: Settlement↑
Wang et al. (2016)	Triaxial test	–	Sand specimens flushed by CO_2 and de-aired water, followed by applying back pressure	S_r, CSR, $\varepsilon^*_{v,air}$, $LRR_{DA=5\%}$	S_r↓: $LRR_{DA=5\%}$↑ S_r↓: CSR↑ $\varepsilon^*_{v,air}$↑: $LRR_{DA=5\%}$↑
Vernay et al. (2016)	Triaxial test	–	CO_2 circulation through the sample, followed by de-aired water circulation	S_r, ε_a, r_u, N_L, Suction	For a given N_L, S_r↓: r_u↓ For a given N_L, S_r↓: ε_a ↓ S_r↓: Suction↑ S_r↓: N_L↑ Even if the soil is unsaturated, liquefaction can occur

Table 1 continiued

References	Analysis type		Partial saturation preparation method	Parameters to be studied	Outcomes and concluding remarks
	Experimental	Numerical			
Bian et al. (2017)	–	Cyclic elastoplastic constitutive model “MODSOL”	By adjusting the porosity of soil and the compressibility of pore fluid, introduced in Koning (1963)	S_r, Δu, K_{aw}, Settlement	$S_r\downarrow$: Rate of Δu generation$\downarrow$ $S_r\downarrow$: $K_{aw}\downarrow$ $S_r\downarrow$: Liquefaction potential$\downarrow$ $S_r\downarrow$: Settlement $\uparrow$ because of the compressibility of air bubbles
Mirshekari and Ghayoomi (2017a, b)	Centrifuge test	–	By steady-state infiltration system	a_{max} (g), S_r, Settlement, Max. lateral deformation	$S_r\downarrow$: Settlement$\downarrow$ $S_r\downarrow$: Max. lateral deformation$\downarrow$ $S_r\downarrow$: a_{max} (g)$\uparrow$
Fioravante et al. (2019)	Triaxial test and centrifuge test	–	With CO_2 circulation, flushing of deaerated water, and adjusting the backpressure	V_p, S_r, N_L, Δu, CRR, ε_a,	$S_r\downarrow$: $N_L\uparrow$ $S_r\downarrow$: CRR$\uparrow$ $S_r\downarrow$: $\varepsilon_a\downarrow$ $S_r\downarrow$: $V_p\downarrow$ $S_r\downarrow$: $\Delta u\downarrow$
Tsukamoto (2019)	Triaxial test	–	Retrieved partially saturated sand samples	r_{n5}, S_r, ε_{v5}, CSR,$\frac{S_{us}}{\sigma_{no}}$	$S_r\downarrow$: $r_{n5}\uparrow$ $S_r\downarrow$: CSR$\uparrow$ $S_r\downarrow$: $\varepsilon_{v5}\downarrow$ $S_r\downarrow$: $\frac{S_{us}}{\sigma_{no}}\uparrow$
Zhang et al. (2019)	Centrifuge test	–	By lowering the groundwater table and controlling the suction	S_r, r_u, σ'_v, Δu	$S_r\downarrow$: $\Delta u\downarrow$ $S_r\downarrow$: $r_u\downarrow$ For a given S_r, $\sigma'_v\uparrow$: $r_u\downarrow$
Chakrabortty et al. (2020)	Triaxial test	Modification of a model to predict r_u	Natural sand samples with various S_r were used	B-value, D_r, Shear modulus, Damping, N, $r_{u,\ max}$, ASR_{peak}	B-value$\downarrow$: Shear modulus$\uparrow$ B-value$\downarrow$: Damping$\uparrow$ N$\uparrow$: $r_{u,\ max}\uparrow$ B-value$\downarrow$: $ASR_{peak}\uparrow$ $D_r\uparrow$: $ASR_{peak}\uparrow$

In the next section, a series of contributions related to liquefaction mitigation due to the induced partial saturation by different methods will be presented in detail.

5 Studies on Liquefaction Resistance of Sands Partially Saturated as a Liquefaction Mitigation Technique

5.1 Experimental Studies

Partial saturation has been accepted as an effective way to counteract liquefaction. Hence, there has been an increased concern in the geotechnical research community to understand the effect of desaturation on soils' dynamic properties. Researchers in this field have done many experimental studies, and different techniques have been adopted to prepare partially saturated sand specimens in these experimental studies. Some of the improved liquefaction responses of soils are considered as key parameters for judgment.

While some studies have focused on reducing excess pore pressure generation in partially saturated soils, others concentrated on the reduced volumetric strain and the settlement of soil surface in the free-field. Also, the applicability of partial saturation as a liquefaction countermeasure under existing structures is of interest. In this section, state-of-the-art approaches in the field will be explained.

5.1.1 Liquefaction Mitigation Owing to the Reduction of Excess Pore Pressure Generation

The most important reason for a liquefaction occurrence is the excess pore pressure generation in soil under undrained cyclic loadings. Therefore, some researchers have focused on the assessment of the efficacy of partial saturation techniques on the reduction of excess pore pressure generation and liquefaction prevention.

Okamura and Teraoka (2006) showed that any reduction in the degree of saturation of soil could dampen the excess pore pressure generation and increase the number of cycles required to reach liquefaction. They injected air into the fully saturated soil and desaturated it to examine desaturation efficiency against liquefaction. They demonstrated that desaturation of liquefiable soil reduces excess pore pressure in the soil layer beneath the foundation. It is noticeable that, even for a fully saturated model under the foundation, no liquefaction was observed. Accordingly, the decrease in the excess pore pressure below the foundation is probably due to the soil's large shear deformation.

Nagao et al. (2007) improved soil layers by injecting microbubbles into the ground. They observed that pore pressure generation in partially saturated sand is less than that of fully saturated sand.

It was concluded by Yegian et al. (2006, 2007), Eseller-Bayat (2009), and Eseller-Bayat et al. (2013a) that for a given strain and relative density, reducing the degree of saturation results in the decrement of the maximum excess pore pressure ratio, $r_{u,\max}$, and could prevent the occurrence of initial liquefaction. Furthermore, the larger $N_{\max}$ (number of cycles to reach $r_{u,\max}$) was observed in partially saturated sand specimens when compared to the fully saturated ones. Figure 6 presents $r_{u,\max}$ as a function of S_r for different ranges of relative density values attained for maximum shear strain, $\gamma_{\max}$, of 0.01, 0.05, 0.1, and 0.2%. All conclusions mentioned above are observable in Fig. 6.

Takemura et al. (2009) prepared partially saturated sand specimens by lowering and raising the groundwater table. Then, they conducted a series of centrifuge model tests to investigate the mechanical behavior of partially saturated sands. They observed that pore water pressure under the footing and in free-field are reduced in partially saturated sands, compared to the fully saturated case. Hence, partial saturation is more effective in the liquefaction mitigation of shallower depths than the deep ones.

He et al. (2013) used denitrifying bacteria to introduce gas bubbles in order to decrease the degree of saturation of sand. They concluded that reducing the saturation degree in the sand is an effective method in the mitigation of liquefaction.

He and Chu (2014), Kavazanjian et al. (2015), He et al. (2016), and Nakano (2018) proposed a microbial desaturation technique that is done by denitrification. According to the triaxial test outputs, lowering the degree of saturation through denitrification resulted in less pore pressure generation under dynamic loading. It also provided higher undrained shear strength.

Nababan (2016) prepared an automated IPS delivery system in a large laminar box to treat sand specimens against liquefaction. A chemical powder (sodium percarbonate) was used to prepare a partially saturated specimen. The prepared specimens were tested under shaking using the large shaker of the laboratory. It was concluded that the excess pore pressures were much smaller than levels that would have liquefied the sand everywhere within the partially saturated specimen.

Gulen and Eseller-Bayat (2017) and Eseller-Bayat and Gulen (2020) prepared small-size samples of partially saturated sands by the IPS method, which decreases the degree of saturation of the sample by generating air/oxygen gas bubbles inside the soil voids. They performed cyclic simple shear tests on these samples in a dynamic simple shear test device with confining pressure (DSS-C) to assess partially

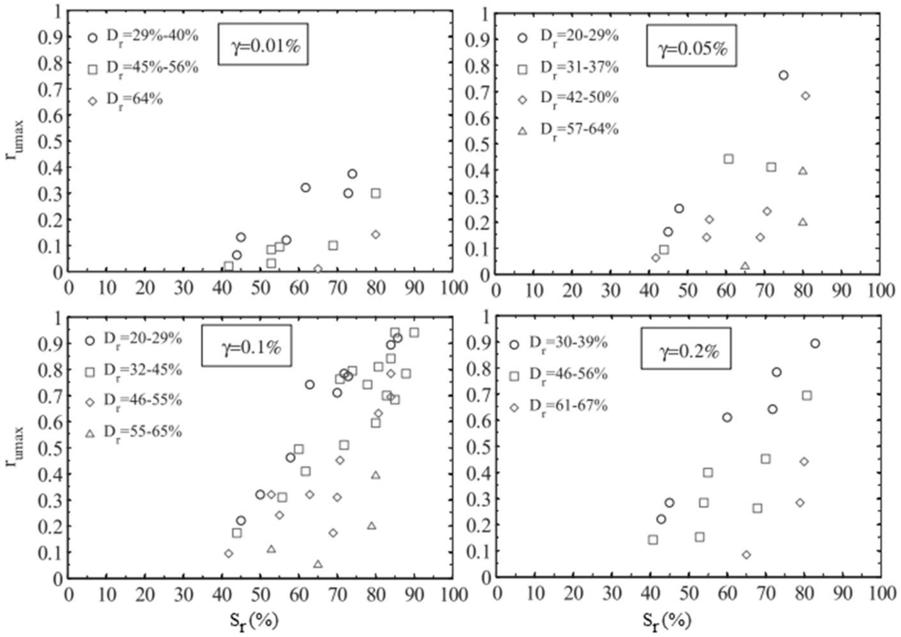

Fig. 6 $r_{u,max}$ measured in partially saturated sand specimens during cyclic simple shear strain tests (modified from Eseller-Bayat et al. 2013b)

saturated sands' undrained dynamic responses at high effective stresses. They compared the results with the experimental results obtained by Eseller-Bayat et al. (2013b). They showed that the excess pore pressure generation decreased with a decreasing degree of saturation under the constant vertical effective stress. Based on the comparisons of the liquefaction test results on small-size and large-size specimens, vertical effective stress greatly influenced the generation of excess pore pressure in partially saturated sands. The excess pore pressure ratio was reduced by increasing vertical effective stress. Furthermore, it was stated that $r_{u,max}$ stabilized and remained at a maximum value less than 1.0 in large-size specimen tests. While in small-size specimen tests, as cyclic shearing continues, some gas/oxygen bubbles can escape or be compressed. Hence, it was observed that r_u generation did not stabilize and continued to increase by the increasing number of cycles (Gulen and Eseller-Bayat 2019; Eseller-Bayat and Gulen 2020).

It is inferred from the DSS-C test setup results that the effect of S_r on r_u generation is more important at higher vertical effective stresses. On the other hand, the increasing effect of vertical effective stress governs the liquefaction strength of partially saturated sands more than the reducing effect of initial hydrostatic water pressures. Accordingly, these results can lead to the application of less reduction in S_r at deeper layers in order to improve the soils through partial saturation. This fact can be considered for fields in which the IPS technique will be implemented for tackling the potential liquefaction. Figure 7 demonstrates that $r_{u,max}$ stabilized at nearly 0.70 in large-size sample tests, while the excess pore pressure ratio nearly reached 0.2, 0.1, and 0.06 under 50 kPa,

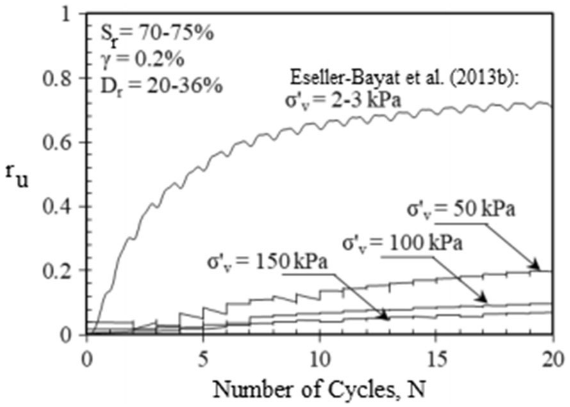

Fig. 7 Comparison of r_u responses of partially saturated sands tested in DSS-C and CSSLB under different vertical effective stresses modified from (Eseller-Bayat and Gulen 2020)

100 kPa, and 150 kPa effective vertical stresses, respectively.

Simatupang and Okamura (2017) and Simatupang et al. (2018) assessed the effect of partial saturation on the liquefaction resistance of sand remediated with carbonate precipitation. They used enzymatically induced calcite precipitation (EICP) as a liquefaction mitigation technique and prepared some sand specimens with a degree of saturation lower than unity. They found out that under cyclic loading, EICP-treated sand resulted in the reduction of the rate of excess pore pressure generation, the increment of shear modulus, and the required cycles to reach liquefaction. Also, they realized that the amounts of calcite precipitation required to provide a given liquefaction resistance could be noticeably reduced by lowering the saturation degree.

Van Paassen et al. (2018) used the denitrification technique to produce biogenic gases inside the saturated soil samples and decrease the degree of saturation. They showed that the high compressibility of the gas dampens the pore pressure generation rate during loadings.

Marasini and Okamura (2015a, b) and Zeybek and Madabhushi (2017a, b) conducted dynamic centrifuge tests to study the performance of desaturation, generated by air injection, in sands beneath the foundations. They checked the excess pore pressure ratio at different locations in the free field and under foundations as a control parameter to judge the efficiency of partial saturation as a liquefaction countermeasure. They showed that air injection efficiently reduced pore pressures generated beneath the foundation. Moreover, the reduction in the degree of soil saturation resulted in the higher accelerations to be transferred to the foundations through non-liquefied soil regions. Finally, their results highlighted the fact that the excess pore pressure ratio decreases by increasing the foundation weight (causing an increase in the effective stress). Hence, even in saturated soils under heavy foundations, liquefaction was not observed.

Kumar et al. (2019) performed centrifuge experiments to study the effects of partial saturation in soil under a shallow foundation subjected to strong sequential motions. The drainage-recharge method was used to induce partial saturation within the liquefiable ground. According to the findings of this experimental study, IPS could reduce the rate of excess pore water pressure generation and its dissipation. Hence, no liquefaction was observed in the case of the partially saturated model. These findings provide evidence that IPS is an effective method for liquefaction mitigation.

Most of the partial saturation techniques discussed in this paper are employed for mitigating the clean sands against liquefaction. Sometimes, the presence of some fine contents (FC) in sandy soils is inevitable. So, the development of partial saturation techniques to employ in sands with fines is critical. Mousavi and Ghayoomi (2020) conducted a series of undrained strain-controlled cyclic simple shear (DSS) tests on untreated and microbial-induced partially saturated (MIPS) clean sands and sands containing various amounts of fine contents to examine the applicability of the MIPS technique in liquefaction prevention. Figure 8a compares the excess pore pressure ratios at various degrees of saturation for clean sands and sands with various fine contents. It shows that MIPS can significantly reduce the developed r_u in sands with fines compared to the clean sand. Figure 8b depicts that MIPS's application to make the sand partially saturated makes it stiffer. Also, under the same conditions (i.e., same D_r, S_r, γ, and σ'_v), the clean sand is stiffer than the sand with fines. Furthermore, the effect of partial saturation is more significant in sands with fines. This result is attributed to higher suction levels developed in finer soils for the same S_r (Mousavi and Ghayoomi 2020).

5.1.2 *Liquefaction Mitigation Owing to the Reduction of Volumetric Strain and Settlements*

According to the experimental studies in the literature, it was concluded that the volumetric strain increment rate for partially saturated sand is slower than that of fully saturated one. Also, since the earthquake-induced settlement of buildings and geotechnical structures resting on liquefiable soils is the leading cause of damage, some experimental studies have been done to assess the applicability of induced partial saturation in preventing these settlements. According to the literature, liquefaction countermeasure techniques effectively reduce the liquefaction-induced ground settlement in a free-field and under existing structures.

Okamura and Soga (2006) performed triaxial tests on partially saturated sand specimens. They showed that the liquefaction resistance depends on three key

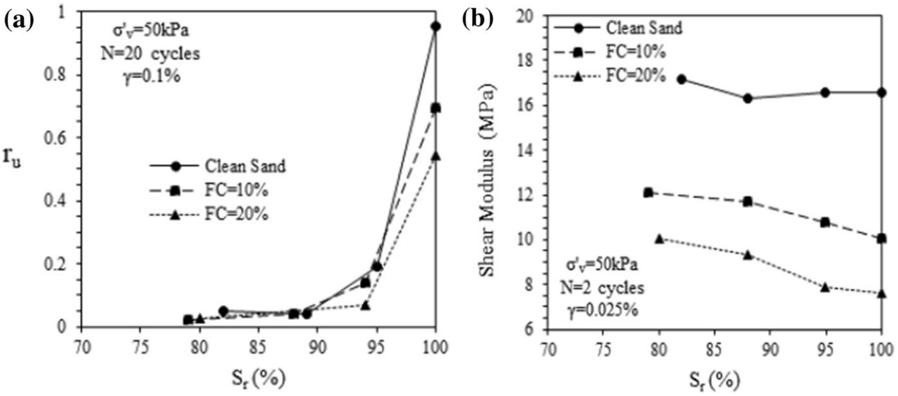

Fig. 8 **a** Variations of the excess pore pressure ratio with the degree of saturation for sands with different fine contents, **b** variations of the secant shear modulus with the degree of saturation for sands with different fine contents. (Data from Mousavi and Ghayoomi 2020)

factors: the degree of saturation, the initial pore pressure, and the initial confining pressure. They claimed that the effect of lowering the degree of saturation on liquefaction resistance is more remarkable for soils under high confining pressure and low initial pore pressure. Finally, they proposed a unique relationship for calculating the liquefaction resistance ratio against the potential volumetric strain. Accordingly, the liquefaction resistance of partially saturated sand normalized with that of fully saturated sand was increased by increasing the potential volumetric strain.

According to the shaking table test results of desaturated soil with and without a rigid foundation by Okamura and Teraoka (2006), the desaturation of a liquefiable soil specimen reduced the foundation's settlement resting on it. Takemura et al. (2009) showed that the footing and free-field settlements were reduced in partially saturated sands compared to the fully saturated case.

Nakai et al. (2015) performed centrifuge shaking table tests of structure-soil models for which dewatering was used for liquefaction mitigation. It was found that by lowering the groundwater table, a non-liquefiable soil layer was formed under the structure. This layer absorbed generated excess pore water pressures in the soil located just below the groundwater table. Hence, it was concluded that dewatering is an effective way to reduce the liquefaction-induced ground settlement and prevent liquefaction under the structure. Although dewatering is known as an effective way to reduce the liquefaction potential, it can cause uneven settlements in the existing structures (Xu et al. 2019).

Dynamic centrifuge test results in a free-field and beneath shallow foundations presented by Marasini and Okamura (2015a, b) and Zeybek and Madabhushi (2017a, b) confirmed that air injection efficiently reduced foundation settlement. Moreover, the reduction in the degree of soil saturation increased the resistance of soil to bearing capacity failure. Referring to the interpretation of triaxial test results conducted by He et al. (2016) and the shaking table tests by He et al. (2013), Nababan (2016), and Peng and Zhang (2017), the volumetric strain of fully saturated sand samples tended to increase at a more accelerating rate than that of imperfectly saturated sand samples. Moreover, the desaturation of a liquefiable soil specimen reduced settlements of the foundation resting on it.

In a centrifuge test, Kumar et al. (2019) constructed two different types of the superstructure as a foundation-structure system; a typical Buffer Tank (BT) and a Flare Stack (FS). Then induced partial saturation was applied within the liquefiable ground through drainage technique. The efficacy of IPS was proved due to the exhibition of a significant amount of maximum potential volumetric compressibility of pore fluid after the sequential motion. IPS reduced the settlement of foundation-structure systems, both during shaking and post-shaking phases. Moreover, more settlement was observed under the heavier structure (FS). These findings are summarized in Fig. 9.

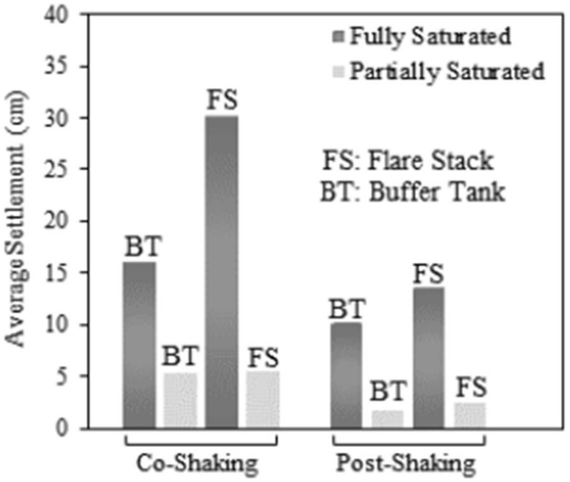

Fig. 9 Co-shaking and post-shaking settlements during strong ground motion (modified from Kumar et al. 2019)

5.2 Analytical Studies

Mitsuji (2008) generated a one-dimensional effective stress computer code to examine the advantage of utilizing partially saturated sand for liquefaction mitigation. He showed that replacing liquefiable saturated sand with a partially saturated sand layer led to the reduction of seismic responses such as the maximum response of velocity, surface settlement, and shearing strain in the ground due to the decrease in the degree of saturation.

Bian and Shahrour (2009) employed Eq. (1) and conducted a numerical investigation of the effect of entrapped gas on the liquefaction resistance of partially saturated sands, with emphasis on the bulk modulus of the gas–water mixture.

They showed that by increasing the gas content (decreasing the degree of saturation in the soil), the bulk modulus of the water–gas mixture decreases. Consequently, the rate of the pore pressure generation decreases, which means a reduction in the liquefaction risk. Also, resistance against liquefaction increased for partially saturated sand.

Gao et al. (2013) conducted computational simulations, based on the extension of Biot's consolidation theory, to investigate desaturation or artificial induction of partial saturation in soils as an effective approach for soil liquefaction mitigation. They used Eq. (1) to simulate the compressibility of the air–water mixture in partially saturated sands with different values of S_r. Their simulation included an equation of motion for solid–fluid mixture called "u-p" in which u and p stand for the displacements of solid phase and pore fluid pressure, respectively. They showed that the number of cycles required to reach liquefaction increases when the degree of saturation decreases.

Eseller-Bayat et al. (2013c) developed an empirical model (RuPSS) to predict $r_{u,max}$ in partially saturated sands subjected to earthquake-induced shear strains. Under earthquake-induced shear strains, the maximum excess pore water pressure ratio ($r_{u,max}$) generated in partially saturated sands can be predicted depending on essential parameters. Eseller-Bayat et al. (2013c) compared their empirical model with the experimental results (see Fig. 10) and showed that their model could predict, with acceptable accuracy, $r_{u,max}$ in sands treated with IPS against liquefaction. Figure 10 demonstrates that the IPS technique can reduce the liquefaction potential of sandy soils under different amplitudes of shear strains.

As discussed in subsection 3.2, the air/gas bubbles in the pore fluid are compressed during the application of shear cycles and absorb the generated excess pore pressure. This can be the main reason for preventing the liquefaction in partially saturated sands. Moreover, in soils with $S_r < 80\%$, matric suction also plays a positive role in reducing the liquefaction potential because it can increase the effective stress. Marasini and Okamura (2015a, b) stated that for a slight change in pore pressure, Δu, the volumetric strains of pore water and air are $\varepsilon_w = \frac{\Delta u}{K_w}$ and $\varepsilon_a = \frac{\Delta u}{K_a}$, respectively. Based on Boyle's law for compressibility of air bubbles, K_a, can be written as: $K_a = u_0 + \Delta u$. A cyclic elastoplastic model (proposed by Oka et al. 1999 for fully saturated sands) based on the nonlinear kinematic hardening rule was used to perform a liquefaction analysis of partially saturated sands.

It is noted that for modeling of partially saturated sands in this model, ε_w is replaced with $\varepsilon_{vf} = \Delta u(\frac{1-S_r}{K_a} + \frac{S_r}{K_w})$. Marasini and Okamura (2015a, b) incorporated the above concepts in an effective-stress-based numerical model to simulate partially saturated sand's liquefaction response in free field and under foundations. Finally, they compared the numerical analysis results with those obtained from centrifuge tests and observed a good agreement between them. Outcomes from their centrifuge tests were explained in Sect. 5.1.1.

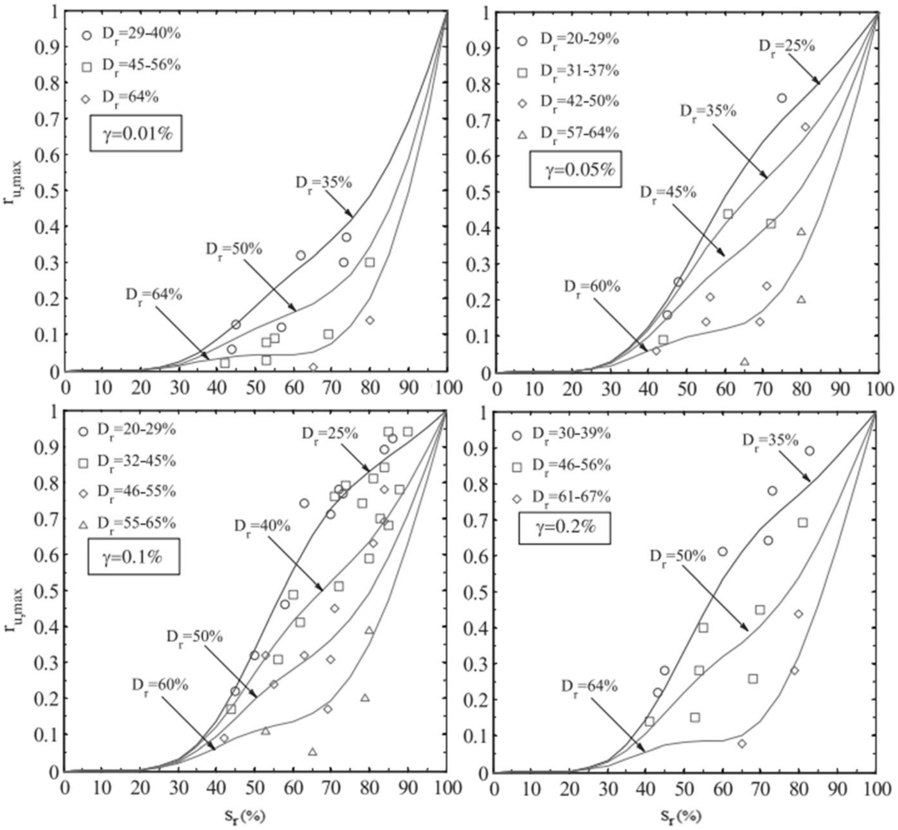

Fig. 10 Comparisons of $r_{u,max}$ from RuPSS model predictions and experimental data tests (modified from Eseller-Bayat et al. 2013c)

Viand and Eseller-Bayat (2017) used FLAC3D software to prepare a numerical model of CSSLB manufactured by Eseller-Bayat et al. (2013b) to simulate the undrained behavior of sand specimens partially saturated by IPS. They used Eq. (1) to model the pore fluid, a mixture of air and water, for sand specimens with various degrees of saturation (40–83%) subjected to several cyclic simple shear strain amplitudes. Excess pore water pressure ratios (r_u) were compared both in numerical and experimental tests. According to the comparisons, the numerical model can simulate, with an acceptable level of accuracy, liquefaction responses obtained in the experiments and confirmed that IPS could decrease the r_u responses of liquefiable sands and prevent liquefaction.

Mele and Flora (2019) and Mele et al. (2019) used triaxial test results presented in the literature to propose a methodology for partially saturated sands' liquefaction analysis. They claim that liquefaction resistance of partially saturated soils is strictly related to the specific energy spent to reach liquefaction. It means that in partially saturated sand, more specific energy should be spent to reach liquefaction. According to Mele and Flora (2019), the total specific energy of deformation, E_{tot}, needed to reach liquefaction is calculated by the summation of two components: the deviatoric specific energy to reach liquefaction, $E_{s,liq}$, and the volumetric specific energy, $E_{v,liq}$.

$E_{s,liq}$ depends on soil state, soil properties, and cyclic stress amplitude, CSR. $E_{v,liq}$ is calculated as follows (Mele and Flora 2019):

$$E_{v,liq} = E_{v,sk,liq} + E_{w,liq} + E_{air,liq} \tag{7}$$

where $E_{v,sk,liq}$, $E_{w,liq}$, and $E_{air,liq}$ are the specific work done to cause the deformation of the soil skeleton, the flow of water, and the flow of air into the pores network, respectively.

As discussed in Sect. 3.2, Vucetic and Dobry (1986) proposed a mathematical model to predict r_u in fully saturated sands (Eq. 5). Although this model performs well for fully saturated soils, it does not include the effect of the degree of saturation. Hence, its accuracy in predicting r_u for partially saturated soils is questionable. Mousavi and Ghayoomi (2020) modified this model and stated it as below:

$$\frac{1}{r_u} = \frac{1 + \frac{K_{aw}}{K_w} \times f \times N \times F \times (\gamma - \gamma_{tvp})^s}{\frac{K_{aw}}{K_w} \times p \times f \times N \times F \times (\gamma - \gamma_{tvp})^s} \quad (8)$$

where K_w is the initial fluid bulk modulus at which the fitting parameters are obtained, and K_{aw} is obtained from Eq. (1). The fitting parameter s is proportional to fines content and equals $(\mathrm{FC} + 1)^{0.1252}$. Furthermore, as mentioned before, F is reversely proportional to V_s in the following form (Mousavi and Ghayoomi 2020):

$$F = \frac{3810}{V_s^{1.55}} \quad (9)$$

Figure 11 compares r_u responses from experimental results to the model given in Eq. (8) to examine this equation's applicability in predicting the excess pore pressure ratios of partially saturated soils in the form of clean sands and sands with fines. It illustrates that the MIPS technique can significantly reduce r_u and be considered as a liquefaction countermeasure. Also, under the same conditions (i.e., N, S_r, γ and σ'_v), clean sands show higher developed r_u than sands containing fines.

Almost all of the numerical and analytical studies discussed in this paper have used Eq. (1) to predict Kaw in the numerical modeling of partially saturated sands' liquefaction behavior. Most recently, Seyedi-Viand and Eseller-Bayat (2021) showed that the accuracy and capability of Eq. (1) to predict Kaw is under question for sands mitigated against liquefaction through induced partial saturation techniques. They used the experimental results presented by Eseller-Bayat (2009) to introduce an alternative empirical function to predict K_{aw} for using in the numerical modeling of liquefaction behavior of induced partially saturated sands. In the first step, a numerical model of CSSLB was constructed, and all the experiments reported by Eseller-Bayat (2009) were simulated, using Eq. (1) for the bulk modulus of the air–water mixture. The second step was devoted to the comparison of numerical and experimental results and showing the dissimilarities between some of the results. Finally, an empirical function for predicting the air–water mixture bulk modulus of induced partially saturated sands, K'_{aw}, was proposed and used in the numerical models. Results obtained with the new proposed bulk modulus were compared with CSSLB test results and the results available in the literature. It was concluded that the proposed function performs well in the numerical models. Equation (10) expresses the proposed function.

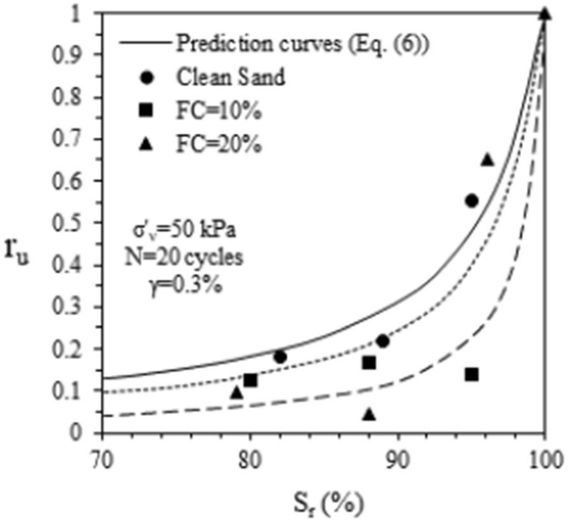

Fig. 11 Comparison of r_u from experimental results to proposed model predictions (Data from Mousavi and Ghayoomi 2020)

$$K'_{aw} = 27.4 \times depth \times e^{(5.5 \times S_r)} \quad (10)$$

where the units for K'_{aw} and the *depth* factor are in kPa and meter, respectively.

Since some of the numerical studies discussed in the present paper are based on limited data, additional research is needed to refine some of the empirical relationships to improve the procedure's overall accuracy for predictive purposes. As a summary, key findings reported in the literature on the assessment of partial saturation as a liquefaction countermeasure are tabulated in Table 2.

6 Studies on the Sustainability of Partial Saturation in Sands

Although the efficacy of induced partial saturation due to the introduction of gas bubbles inside the soil voids has been proven as a liquefaction countermeasure by many experimental studies, the durability of these entrapped air bubbles is still under question. Most

Table 2 Overview of key findings reported in the literature from studies on partial saturation as a liquefaction countermeasure

References	Analysis type		Partial saturation preparation method	Parameters to be studied	Outcomes and concluding remarks
	Experimental	Numerical			
Okamura et al. (2006)	Undrained cyclic shear tests	–	Desaturation by air injection	CSR, N, S_r	For a given N, $S_r\downarrow$: CSR$\uparrow$
Okamura and Teraoka (2006)	Shaking table test	–	Desaturation by air injection	ε_v^*, N_L, P_a, r_u, S_r, Width of desaturated zone, Foundation settlement, Q	$\varepsilon_v^*\uparrow$: $N_L\uparrow$ $P_a\uparrow$: $N_L\downarrow$ Width of desaturated zone$\uparrow$: Foundation settlement$\downarrow$ Q$\uparrow$: $r_u\downarrow$ $S_r\downarrow$: $r_u\downarrow$ $S_r\downarrow$: Foundation settlement$\downarrow$
Nagao et al. (2007)	Triaxial test	–	By injecting micro-bubbles into the saturated sample	r_u, CSR, N	For a given N, $S_r\downarrow$: CSR$\uparrow$
Yegian et al. (2006, 2007)	Cyclic simple shear liquefaction box on shaking table	–	Using the process of electrolysis to produce oxygen and hydrogen gases in the fully saturated sand sample	$r_{u,max}$, Settlement, ε_a	$S_r\downarrow$: $r_{u,max}\downarrow$ $S_r\downarrow$: Settlement$\downarrow$ $S_r\downarrow$: $\varepsilon_a\downarrow$
Mitsuji (2008)	–	One-dimensional effective stress analysis	By adjusting pore water pressure building-up parameters	CSR, N_L, r_u, a_{max} (g)	$S_r\downarrow$: $N_L\uparrow$ $S_r\downarrow$: $r_u\downarrow$ $S_r\downarrow$: a_{max} (g)$\uparrow$ $S_r\downarrow$: CSR$\uparrow$
Hatanaka and Masuda (2009)	Triaxial test	–	Reducing S by injecting air bubbles into the soil	V_p, S_r, N, CSR	$S_r\downarrow$: $V_p\downarrow$ For a given N, $S_r\downarrow$: CSR$\uparrow$ $S_r\downarrow$: Liquefaction potential$\downarrow$
Takemura et al. (2009)	Centrifuge test	–	Decreasing the degree of saturation by lowering the water table	Δu, Q, Settlement, Foundation settlement	$S_r\downarrow$: Foundation settlement$\downarrow$ $S_r\downarrow$: Settlement$\downarrow$ Q$\uparrow$: $\Delta u\downarrow$ Q$\uparrow$: Foundation settlement$\uparrow$
Okamura et al. (2011)	Triaxial test	Numerical analyses with a gas–liquid two-phase flow simulator	Desaturation by air injection	CSR, N, S_r, LRR,ε_v^*	For a given N, $S_r\downarrow$: CSR$\uparrow$ For a given S_r, $\varepsilon_v^*\uparrow$: LRR$\uparrow$
Eseller-Bayat (2009, 2013a, b)	Cyclic simple shear liquefaction box on shaking table	–	Wet pluviation sodium perborate monohydrate mixed with Ottawa sand	N_{max}, $r_{u,max}$, V_p, γ, D_r	$S_r < 90\%$: $r_{u,max} < 1.0$ regardless of γ and N For a given S_r and γ, $D_r\uparrow$: $r_{u,max}\downarrow$ For a given S_r and D_r, $\gamma\uparrow$: $r_{u,max}\uparrow$ For a given D_r and γ, $S_r\downarrow$: $r_{u,max}\downarrow$

Table 2 continued

References	Analysis type		Partial saturation preparation method	Parameters to be studied	Outcomes and concluding remarks
	Experimental	Numerical			
					$S_r\downarrow$: $V_p\downarrow$
Eseller-Bayat et al. (2013c)	–	Introduction of an empirical model (RuPSS) to predict r_u in partially saturated sands	Using experimental data performed by Eseller-Bayat (2009)	N_{max}, $r_{u,max}$, γ, D_r, S_r	For a given γ and D_r, $S_r\uparrow$: $r_{u,max}\uparrow$ For a given S_r and D_r, $\gamma\uparrow$: $r_{u,max}\uparrow$ For a given γ and S_r, $D_r\uparrow$: $r_{u,max}\downarrow$
Gao et al. (2013)	–	Developing a computational model to study the influence of S on the soil liquefaction resistance	Extension of Biot's consolidation theory to desaturated pore fluid conditions	S_r, N_L, Δu, C_{aw}	$S_r\downarrow$: $C_{aw}\uparrow$ $S_r\downarrow$: $N_L\uparrow$ $S_r\downarrow$: $\Delta u\downarrow$ $S_r\downarrow$: Liquefaction potential↓
He et al. (2013)	Triaxial test, 1−g shaking table test	–	Using denitrifying bacteria to generate gas bubbles in sand	S_r, D_r, $\Delta\varepsilon_{vd}$, r_u, Settlement, Amplification of acceleration	For a given D_r, $S_r\downarrow$: $r_{u,max}\downarrow$ For a given S_r, $D_r\downarrow$: $r_{u,max}\uparrow$ For a given D_r, $S_r\downarrow$: $\Delta\varepsilon_{vd}\downarrow$ For a given D_r, $S_r\downarrow$: Settlement↓ $r_u\uparrow$: $\Delta\varepsilon_{vd}\uparrow$ 6. For a given D_r, $S_r\downarrow$: Amplification of acceleration↓
He and Chu (2014)	Triaxial test	–	Microbial denitrification to generate gas	S_r, Δu, ε_a, $r_{u,max}$, q, CSR, D_r,	For a given q, $S_r\downarrow$: $\varepsilon_a\uparrow$ For a given ε_a, $S_r\downarrow$: $\Delta u\downarrow$ For a given D_r, $S_r\downarrow$: $r_{u,max}\downarrow$ For a given D_r, $S_r\downarrow$: CSR↑
Kavazanjian et al. (2015)	Triaxial test, cyclic simple shear tests	–	By denitrification and production of N_2 gas	CSR, N_L, S_r, V_p, Δu, ε_a	For a given N_L, $S_r\downarrow$: CSR↑ S_r (or B-value)↓: $V_p\downarrow$ $\varepsilon_a\uparrow$: $\Delta u\uparrow$
Marasini and Okamura (2015a, b)	Centrifuge test	Using a two-phase, fully coupled finite-element code	Air-injection	r_u, Foundation settlement, Q	1. $S_r\downarrow$: $r_u\downarrow$ 2. $S_r\downarrow$: Foundation settlement↓ 3. Q↑: Foundation settlement↑ 4. Q↑: $r_u\downarrow$
Nakai et al. (2015)	Centrifuge test	Using one-dimensional finite element method based on the "Ramberg Osgood" type constitutive relationship	Dewatering	Depth of dewatering, Δu	Depth of dewatering↑: $\Delta u\downarrow$

Table 2 continued

References	Analysis type		Partial saturation preparation method	Parameters to be studied	Outcomes and concluding remarks
	Experimental	Numerical			
He et al. (2016)	Triaxial test, 1−g shaking table test	–	Microbial denitrification to generate gas	S_r, Δu, ε_a, $r_{u,max}$, q, CSR, D_r, $\Delta\varepsilon_{vd}$, Settlement,	For a given q, $S_r\downarrow$: $\varepsilon_a\uparrow$ For a given ε_a, $S_r\downarrow$: $\Delta u\downarrow$ For a given D_r, $S_r\downarrow$: $r_{u,max}\downarrow$ For a given D_r, $S_r\downarrow$: CSR↑ $S_r\downarrow$: Settlement↓ and $\Delta\varepsilon_{vd}\downarrow$
Nababan (2016)	Using a laminar box on shaking table	–	By injecting the solution of sodium percarbonate into the fully saturated sand	Δu, Settlement	$S_r\downarrow$: $\Delta u\downarrow$ $S_r\downarrow$: Settlement↓
Gulen and Eseller-Bayat (2017, 2019)	Dynamic simple shear test	–	Mixing sodium percarbonate with dry sand and water	S_r, γ, σ'_v, D_r, $r_{u,max}$	For a given S_r, γ and D_r, $\sigma'_v\uparrow$: $r_{u,max}\downarrow$ For a given S_r, σ'_v and D_r, $\gamma\uparrow$: $r_{u,max}\uparrow$ For a given σ'_v, γ and D_r, $S_r\downarrow$: $r_{u,max}\downarrow$
Peng and Zhang (2017)	Shaking table test	–	By the biogas desaturation method	S_r, Δu, Settlement, ε_v	$S_r\downarrow$: $\Delta u\downarrow$ $S_r\downarrow$: Settlement↓ $S_r\downarrow$: $\varepsilon_v\downarrow$
Viand and Eseller-Bayat (2017)	–	Using Finn model in FLAC3D software	Using the equation for K_{aw} introduced in Koning (1963)	S_r, r_u	1. $S_r\downarrow$: $r_u\downarrow$
Simatupang and Okamura (2017)	Triaxial test	–	Using enzymatically induced calcite precipitation (EICP)	S_r, LRR, σ'_v, CSR, r_u, N_L, N	$S_r\downarrow$: $N_L\uparrow$ For a given N_L, $S_r\downarrow$: CSR↑ For a given N and S_r, $\sigma'_v\downarrow$: CSR↑ For a given σ'_v, $S_r\downarrow$: LRR↑
Van Paassen et al. (2018)	Triaxial test	–	By producing biogenic gas with the denitrification method	S_r, K_{aw}	$S_r\downarrow$: $K_{aw}\downarrow$
Zeybek and Madabhushi (2017a, b .c)	Centrifuge test, 1−g vertical sand column test	–	By air injection	S_r, Q, Δu, Settlement	$S_r\downarrow$: $\Delta u\downarrow$ For a given S_r, Q↑: Settlement↓ $S_r\downarrow$: Free-field settlement↓ For a given S_r, Q↑: $\Delta u\downarrow$ The durability of air bubbles in the soil layers is reliable for long-term application

Table 2 continued

References	Analysis type		Partial saturation preparation method	Parameters to be studied	Outcomes and concluding remarks
	Experimental	Numerical			
					Most part of the settlement occurs in co-seismic stage, in comparison to post-shaking stage
Nakano (2018)	Sand column test	–	Through microbe-induced denitrification	Δu, S_r	S_r↓: Δu↓
Simatupang et al. (2018)	Triaxial test	–	Dry sand mixed with a certain amount of solution of cementation materials comprising $CaCl_2$	C_L, Calcite content, σ'_v, LRR, G_0	For a given calcite content, S_r↓: C_L↑ For a given LRR, S_r↓: calcite content↓ For a given σ'_v, S_r↓: LRR↑ For a given σ'_v, S_r↓: G_0↑
Kumar et al. (2019)	Centrifuge test	–	Drainage-recharge method	S_r, r_u, Settlement, a_{max} (g), $\Delta\varepsilon_{vd}$, TF amp., γ_{max}	S_r↓: TF amp.↑ S_r↓: r_u↓ S_r↓: Amplification of a_{max} (g)↑ S_r↓: γ_{max}↓ S_r↓: Settlement↓ and $\Delta\varepsilon_{vd}$ ↓
Mele and Flora (2019); Mele et al. (2019)	Triaxial test	–	By adjusting the back pressure level during the test	CSR, CRR, N_L, Δu, S_r, $E_{s,liq}$	For a given N_L, S_r↓: CRR↑ S_r↓: $E_{s,liq}$↑ CSR↓: $E_{s,liq}$↑ CRR↑: $E_{s,liq}$↑
Hu et al. (2020)	One-dimensional device under hydrostatic condition, hydraulic gradient flow condition and horizontal excitation condition	–	Using denitrification method to introduce biogas bubbles	Permeability,S_r	The durability of air bubbles in the soil layer under hydrostatic conditions was reliable for long-term application When the hydraulic gradient was constant, S_r remained constant after a small increment The durability of air bubbles in the soil layer under applied excitations was reliable The permeability of partially saturated soil remained constant with time, after a fluctuation
		–			

Table 2 continued

References	Analysis type		Partial saturation preparation method	Parameters to be studied	Outcomes and concluding remarks
	Experimental	Numerical			
Eseller-Bayat and Gulen (2020)	Dynamic simple shear test		Wet pluviation of dry sand into a water-sodium percarbonate mixture	N, S_r, γ, σ'_v, D_r, $r_{u,max}$	For a given S_r, γ and D_r, $\sigma'_v\uparrow$: $r_{u,max}\downarrow$ For a given S_r, σ'_v and D_r, $\gamma\uparrow$: $r_{u,max}\uparrow$ For a given σ'_v, γ and D_r, $S_r\downarrow$: $r_{u,max}\downarrow$ The beneficial effect of S_r on r_u generation is more significant at higher σ'_v values In small specimens, as cyclic shearing continues, gas bubbles can escape and/or be compressed. Hence, in small-sample tests, the liquefaction behavior of partially saturated samples could be examined up to at most N = 50 cycles
Mousavi and Ghayoomi, (2020)	Dynamic simple shear test	Modification of a model to predict r_u	Desaturation using microbial denitrification process	N, S_r, γ, σ'_v, D_r, $r_{u,max}$, FC, ε_v, shear modulus	For a given S_r, σ'_v, D_r and N, $\gamma\uparrow$: $r_{u,max}\uparrow$ For a given N, σ'_v, γ and D_r, $S_r\downarrow$: $r_{u,max}\downarrow$ For a given S_r, σ'_v, D_r, N and γ, FC$\uparrow$: $r_{u,max}\downarrow$ For a given S_r, σ'_v, D_r, N and γ, FC$\uparrow$: $\varepsilon_v\downarrow$ For a given S_r, σ'_v, D_r, N and γ, FC$\uparrow$: Shear Modulus$\downarrow$
Seyedi-Viand and Eseller-Bayat (2021)	–	Introduction an empirical function to predict air–water mixture bulk modulus	Using Finn model in FLAC3D software to simulate experimental tests	K'_{aw}, S_r, $r_{u,max}$	$S_r\downarrow$: $r_{u,max}\downarrow$ $K'_{aw}\downarrow$: $r_{u,max}\downarrow$

researchers think that entrapped air may escape out of the soil after a short while. To address this concern, some experimental efforts were performed, and the results confirmed that the longevity of entrapped air in the soil is acceptable.

Yegian et al. (2006, 2007) used the drainage-recharge method and prepared a column of loose sand containing some entrapped air. After nearly 63 weeks, they observed that the sand's degree of saturation only increased by 1%.

Okamura and Teraoka (2006) and Okamura et al. (2006) showed that gas bubbles introduced in the sand during the process of the installation of soil compaction piles in an understudied field could remain entrapped for up to 26 years after the installation of the piles.

Eseller-Bayat et al. (2013b) conducted some tests to monitor the degree of saturation of the specimen under long-term hydrostatic conditions. They showed that the average degree of saturation only increased by 2% after 115 weeks due to the escape and/or dissolution of gas (air) bubbles from only the top 5.0 cm of the specimen. Additional tests were conducted to control the sustainability of entrapped air under vertical upward hydraulic gradients. The results demonstrated that the upward flow through the partially saturated specimen did not have a significant effect on changing the degree of saturation. Furthermore, the sustainability of the partial saturation under the horizontal cyclic base shaking was also investigated by exciting the specimen fixed on a small shaking table. It was shown that applied base excitation of up to 1 g for over 10,000 cycles did not significantly change the degree of saturation in a partially saturated specimen (see Fig. 12a), providing evidence that air may remain entrapped even after any shaking.

Zeybek and Madabhushi (2017c) undertook multiple series of 1 g vertical sand column and high-g centrifuge tests to investigate the sustainability of entrapped air bubbles inside the voids of partially saturated sand samples.

The test results showed that the majority of entrapped air bubbles in soils could persist under several simulated field circumstances for an extended period of time, representing the long-term consistency of the IPS mitigation technique.

Hu et al. (2020) devised a one-dimensional device to conduct a series of sustainability tests on biogas bubbles in pores of sand in order to assess the long-term sustainability of biogas bubbles. They prepared partially saturated sand samples by introducing biogas bubbles inside the fully saturated sand. The sustainability of the bubbles was monitored under three different conditions: under hydrostatic condition, hydraulic gradient flow condition, and horizontal excitation condition. After 72 weeks of monitoring sand samples under hydrostatic conditions, biogas bubbles existed stable in soil pores. As for the existence of hydraulic gradient flow, when the hydraulic gradient was constant, the degree of saturation remained constant after a small increment. It was noted that the degree of saturation did not increase to 100% because seepage did not occur constantly.

Finally, the sustainability of gas bubbles was examined under horizontal excitations with different amplitudes. It was observed that under applied harmonic waves up to 2 m/s^2 amplitude and for 41,200 cycles, the change in S_r was insignificant (see Fig. 12b).

7 Conclusion

In the past few decades, various types of experimental and numerical studies have been performed to assess the liquefaction response of partially saturated sands. Until the year 2006, partial saturation in sand was studied as the misinterpretation of fully saturated samples' liquefaction strength due to the imperfect

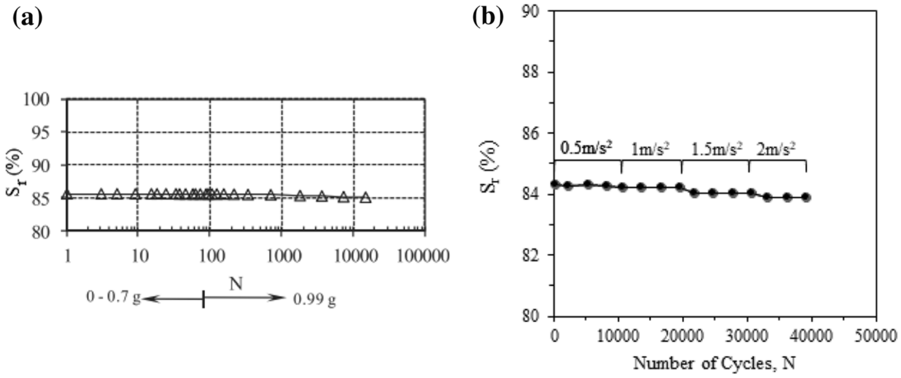

Fig. 12 Degree of saturation variation under base shaking **a** modified from Eseller-Bayat et al. (2013b), **b** Hu et al. (2020)

saturation of samples in laboratory tests. On the other hand, the interpretation of the liquefaction analysis of imperfectly saturated soils has led researchers to deduce that reducing the degree of saturation results in a higher number of cycles to reach liquefaction. Then, in later studies, it was thought that partial saturation is a way to increase the resistance against the potential liquefaction of saturated soils.

Starting from 2006, new viewpoints were generated on the increased liquefaction resistance of saturated soils due to the introduction of some amount of entrapped air in the voids. By focusing on experimental and numerical studies in the field of liquefaction hazards and mitigation, it appears that a common agreement has been established among researchers: partial saturation is an efficient and economical way to mitigate liquefaction. It means that when a saturated soil turns into partially saturated, even under a higher number of applied cyclic loadings, it will not be liquefied.

To summarize, this review study provides valuable information that can help geotechnical engineers in the application of partial saturation for liquefaction mitigation. First, studies on the misinterpretation of liquefaction resistance of sands due to imperfect saturation was presented. Next, experimental and numerical studies on partially saturated sands were summarized. Then, it was shown that partial saturation was considered as a liquefaction countermeasure. Finally, experimental and numerical studies on the liquefaction resistance of partially saturated sands as a liquefaction countermeasure were presented.

In light of the studied literature, some noticeable findings are summarized as below:

1. Any reduction in the degree of saturation of fully saturated sandy soils results in the increment of the shear strength, the bearing capacity, and the soil's liquefaction resistance.
2. In the case of settlement responses in a free-field and under foundations resting on liquefiable soils, reducing the degree of saturation leads to a decrement in the free-field and foundation settlements. However, it results in more accelerations transferred to the foundation.
3. Experimental test results have shown that the majority of entrapped air bubbles in partially saturated soils can persist under several simulated field circumstances for an extended period of time, representing the long-term consistency of the induced partial saturation mitigation techniques.

Although the efficiency of IPS in liquefaction mitigation has been proven experimentally, the implementation of this technique in real-life cases and its evaluation in reducing the liquefaction potential in the field is of interest. More comprehensive and numerical studies can validate this method's applicability and inspire the conception and development of the new tools to design and implement partial saturation in geotechnical engineering projects.

8 Recommendations for Future Research

An exhaustive literature review has been conducted in this paper to collect almost all of the studies performed on partial saturation as a liquefaction countermeasure. However, there are possible gaps or openings for future research and contribution to the topic, some of which are listed as below:

- Almost all of the experimental studies, numerical models and predictive functions to estimate the dynamic response of partially saturated sands under cyclic loadings are based on small-scale test setups (i.e., triaxial tests, DSS tests, etc.) and/or model tests. It is crucial to plan and conduct real-size field tests to examine the accuracy and applicability of these functions and models.
- According to small-scale tests, the generation of r_u in partially saturated specimens continually increases with the number of cycles, and it is not stabilized at a constant $r_{u,max}$ less than unity. Since the air bubbles in small specimens can be compressed or escape by continuing the application of cyclic shearing, designing novel test setups or equipment (i.e., membranes, containers, etc.) to overcome the mentioned problem in order to get more reliable results in the experimental studies can be a research program in the future.
- Air–water mixture bulk modulus plays a significant role in defining the properties of partially saturated sands in the numerical models. So, the available models to predict this parameter can be validated and improved through experimental studies.

- It has been shown and proved in the literature that $r_{u,max}$ in partially saturated sands does not reach unity under different amplitudes of cyclic shear strain in model tests and numerical analysis. This finding should be in soils improved by partial saturation against liquefaction in real size field tests.
- There are a series of methods to improve the soils against liquefaction. Application of these methods for the existing buildings should not disturb the soils under foundations. It is required to devise and employ non-destructive improvement methods to implement under existing buildings rested on soils prone to liquefaction.
- It has been approved that any reduction in the degree of saturation reduces the liquefaction risk. Hence, it is crucial to find a way to define the required amount of reduction in the degree of saturation to guarantee complete mitigation of liquefaction.
- For numerical modeling of partially saturated sands in the literature, the soil model properties usually are calibrated based on the cyclic resistance ratio, CRR, versus the number of cycles to reach liquefaction, N_L, curves. However, it has been shown that partially saturated sands do not liquefy under cyclic loadings. So, these curves do not make sense for partially saturated sands. In conclusion, more experimental studies are required to calculate the CRR of partially saturated sands under different cyclic loadings.
- During the last decades, severe damages both during and after strong earthquakes have been monitored in many buildings in the world. These damages usually appear in the form of excessive settlements under foundations and large deformations in the buildings. Hence, the liquefaction analysis of the soils under existing buildings and properly selecting the soil improvement methods against liquefaction should be accomplished based on performance-based design.
- For complete field application of partial saturation techniques as liquefaction mitigation methods, new tools and technologies should be developed to measure the induced degree of saturation in the field as well as the performance of the implemented technique.

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Declartions

Conflict of interest None.

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