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Liquefaction and undrained cyclic behaviour in fully and partially saturated sands

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ABSTRACT: The reduction in the degree of saturation is considered one of the most efficient methods to improve the cyclic resistance of sands. Hence, one of the most promising liquefaction mitigation techniques involves the induction of partial saturation. This paper compiles and analyses a series of cyclic triaxial tests results conducted in different sands under different degrees of saturation to assess the performance of induced partial saturation on the undrained cyclic behaviour of sands. The results confirmed the improvement in liquefaction resistance and cyclic behaviour of the five sands. This finding accentuates the effectiveness of induced partial saturation as a method for mitigating the liquefaction phenomenon. To conclude, a novel approach to quantify the effectiveness of induced partial saturation for the improvement of liquefaction resistance and undrained cyclic behaviour in sands is suggested.

1. INTRODUCTION

Earthquake-induced liquefaction is one of the most complex and instability process characterised by the rapid loss of the strength and stiffness of the soil (Ishihara 1993). The instability is caused by the accumulation of pore pressure build-up under cyclic loading, which leads to an effective stress equal to zero. The pore pressure build-up causes the loss of contact between soil particles. Typically, the phenomenon occurs in soil deposits composed of saturated clean sands. Under this context, the reduction in the degree of saturation helps to mitigating the damage caused by earthquake-induced liquefaction.

Induced partial saturation (IPS) techniques have shown promising results for liquefaction mitigation (Eseller-Bayat 2009; Flora et al. 2020; Towhata 2021; Astuto et al. 2023). The IPS allow for mitigating the liquefaction phenomena by increasing the compressibility of the pore fluid, which changes its bulk modulus. Such a process involves the generation of gas in the porous medium of the soil skeleton. The presence of the gas (e.g. air) in the pore fluid decreases the degree of saturation (*Sr*), reducing the pore pressure build-up during cyclic loading.

This study analyses an existing database of laboratory test results to assess the liquefaction resistance and cyclic behaviour in fully and partially saturated sands. For this purpose, experimental data in well-characterised sands at various degrees of saturation (i.e., 80% < *Sr* < 100%) were compiled. These results clearly confirm an increase in the liquefaction resistance in partially saturated conditions. However, such increase is different for each sand. Therefore, an analysis based on the estimation of normalised cyclic resistance (NCR) was performed to compare and quantify the improvement in liquefaction resistance provided by the IPS technique in the addressed sands.

2. BACKGROUND ON IPS TECHNIQUES

The induced partial saturation (IPS) has emerged as a new cost-effective and environmentally friendly method for liquefaction mitigation. This method is relatively inexpensive and relatively easy to implement since it involves only the injection or production of gas into the soil deposit, improving the soil response of the soil during cyclic loading (He et al., 2014). Furthermore, IPS techniques can be applied in both free-field and urban areas without causing vibrations that may affect the structural performance of surrounding buildings and critical infrastructures, such as houses, hospitals, bridges and pipelines (Huang and Wen 2014).

The improvement of liquefaction resistance in partially saturated soils can be attributed to two key mechanisms (Cordeiro et al., 2022): (i) matric suction and (ii) reduction of fluid compressibility. Matric suction plays a role in increasing the effective stress, thus the soil stiffness and strength (Bishop & Blight, 1963). However, its contribution to liquefaction resistance is considered negligible, since the maximum matric suction observed in clean and well graded sands is lower than 5 kPa (Fredlund, 2006). In turn, the reduction of fluid compressibility emerges as the primary mechanism that improves the liquefaction resistance of granular soils. This is achieved by the presence of occluded air bubbles, which absorb the pore pressure build-up generated during seismic activity, leading to a reduction in soil volume (Pietruszczak & Pande, 1996). Hence, the cyclic resistance improvement from the decrease in the bulk modulus of the fluid due to the presence of these air bubbles (Cordeiro et al., 2022; Mele et al., 2022). Figure 1 shows a digital image of the air bubbles generated in the soil after applying IPS.

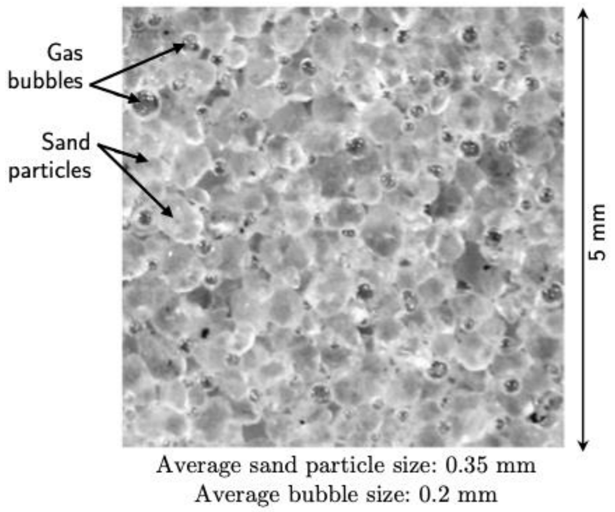

Figure 1. Digital image of desaturated Ottawa sand after applying IPS (after Eseller-Bayat, 2009)

Diverse authors reported that the application IPS technique may create a desaturated condition into the soil between 68% to 98% (Okamura et al. 2011; Rebata-Landa and Santamarina 2012; Mousavi et al. 2021). Notwithstanding, the reduction in *Sr* depends on the specific IPS technique adopted to improve the liquefaction resistance and cyclic behaviour of the soil. The following techniques can be used to implement the IPS in soil deposits for liquefaction mitigation:

- air injection (Marasini and Okamura 2015; Zeybek and Madabhushi 2018);
- water electrolysis (Yegian et al. 2007; Zhang et al. 2020);
- chemical desaturation (Eseller-Bayat et al. 2013);
- bio-desaturation or microbial desaturation (He et al. 2013; Astuto 2021; Wang et al. 2021a).

The effectiveness of these techniques in soil desaturation can be influenced by the depth of the treated soil and the amount of gas generated by each technique. Therefore, the outcomes achieved with each technique will depend on the specific area and the desired final *Sr* in the treated zone (Towhata 2021). However, the degree of partial saturation achieved in the soil can significantly impact the effectiveness of the technique. Achieving and maintaining a specific saturation level throughout the project duration can be challenging. Factors such as soil properties, groundwater conditions and site-specific characteristics can affect the uniformity and stability of the induced partial saturation (Flora et al. 2020). Therefore, the long-term performance and durability of IPS require consideration. Other issues such as gas migration, long-term stability, and the potential for gas leakage over time should be monitored to ensure the sustained effectiveness of the IPS technique (Okamura et al., 2011; Wang et al., 2021; Zeybek & Madabhushi, 2018).

3. MATERIALS AND METHODS

To study the IPS effects on liquefaction resistance and cyclic behaviour of sands, a series of experimental results in fully and partially saturated conditions were compiled from the literature. These results addresses the cyclic resistance curves of five well-characterised sands, namely Ottawa (Sherif et al. 1977), Niigata (Ishihara et al. 1998), Sile (Zeybek 2022) Toyoura (Tsukamoto et al. 2002) and TP-Lisbon sand (Molina-Gómez et al. 2023).

Figure 2 presents the grain size distribution (GSD) of the sands. Table 1 provides the physical properties of the sands. The physical properties are specific gravity of solid particles (Gs), maximum void ratio (e_{max}) and minimum void ratio (e_{min}). Besides, Table 1 presents the fines content (FC) and the parameters of GSD curve, i.e. coefficients of curvature and uniformity (Cc and Cu). All sands were classified as poorly graded sands (SP).

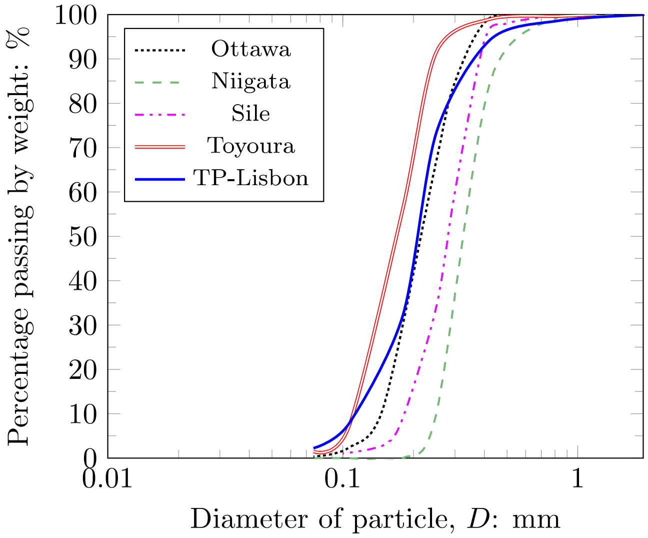

Figure 2. Grain size distributions

Table 1 Physical properties

Sand	*Gs*	e_{max}	e_{min}	FC (%)	*Cc*	*Cu*
Ottawa	2.65	0. 78	0.51	0.17	0.95	1.71
Niigata	2.65	0.98	0.65	0.21	1.01	1.62
Sile	2.65	0.89	0.57	0.21	0.97	1.35
Toyoura	2.66	0.97	0.62	0.27	0.98	1.57
TP-Lisbon	2.66	1.01	0.64	2.27	1.13	1.69

The experimental data presented herein was obtained from cyclic triaxial tests (CTx) conducted under various testing conditions, including different mean effective stress (p'_0) and relative density (*Dr*). It is worth noting that obtaining data with identical testing conditions was challenging due to the unique characteristics and conditions of each experimental program, since the five studies addressed diverse and specific features to investigate the cyclic response of each sand. However, by compiling data from various studies, a comprehensive analysis was performed to explore the *Sr* effects on liquefaction resistance and cyclic behaviour of sands. Table 2 specifies the CTx testing conditions of the databases analysed herein.

Table 2 CTx testing conditions

Sand	p'_0 (kPa)	*Dr* (%)	Reference
Ottawa	50	40	Sherif et al. (1977)
Niigata	118	62	Ishihara et al. (1998)
Sile	100	40	Zeybek (2022)
Toyoura	98	60	Tsukamoto et al. (2002)
Toyoura	98	40	Tsukamoto et al. (2002)
TP-Lisbon	50	30	Molina-Gómez et al. (2023)

4. RESULTS AND DISCUSSION

Figure 3 shows the cyclic resistance curves for the five sands for different *Sr*. These curves were derived by identifying the number of cycles to reach the liquefaction onset (N_L) for different cyclic stress ratios (CSR). In this study, CSR was considered equivalent to the cyclic resistance ratio (CRR), which was defined as follows:

$$CSR = CRR = \frac{q}{2p'_0} \qquad (1)$$

where *q* is the deviatoric stress. The cyclic loading of all tests was applied by a continuous sinusoidal signal with a frequency between 0.1 Hz and 1 Hz and diverse amplitudes of *q*, which involved cycles of compression and extension loading, allowing for the inversion of the principal stresses during testing.

According to the authors (Sherif et al. 1977; Ishihara et al. 1998; Tsukamoto et al. 2002; Zeybek 2022; Molina-Gómez et al. 2023), the liquefaction onset was identified using the double strain amplitude criterion. Such a criterion designates the liquefaction onset when the soil achieves axial strains higher than 5% in compression and extension cycles during CTx testing. From the experimental data, a series of parallel power laws were derived to describe the cyclic resistance ratio for the *Sr* studied in each sand. Table 3 indicates the parameters defining all power laws that describe the cyclic resistance curves for different *Sr* in all sands.

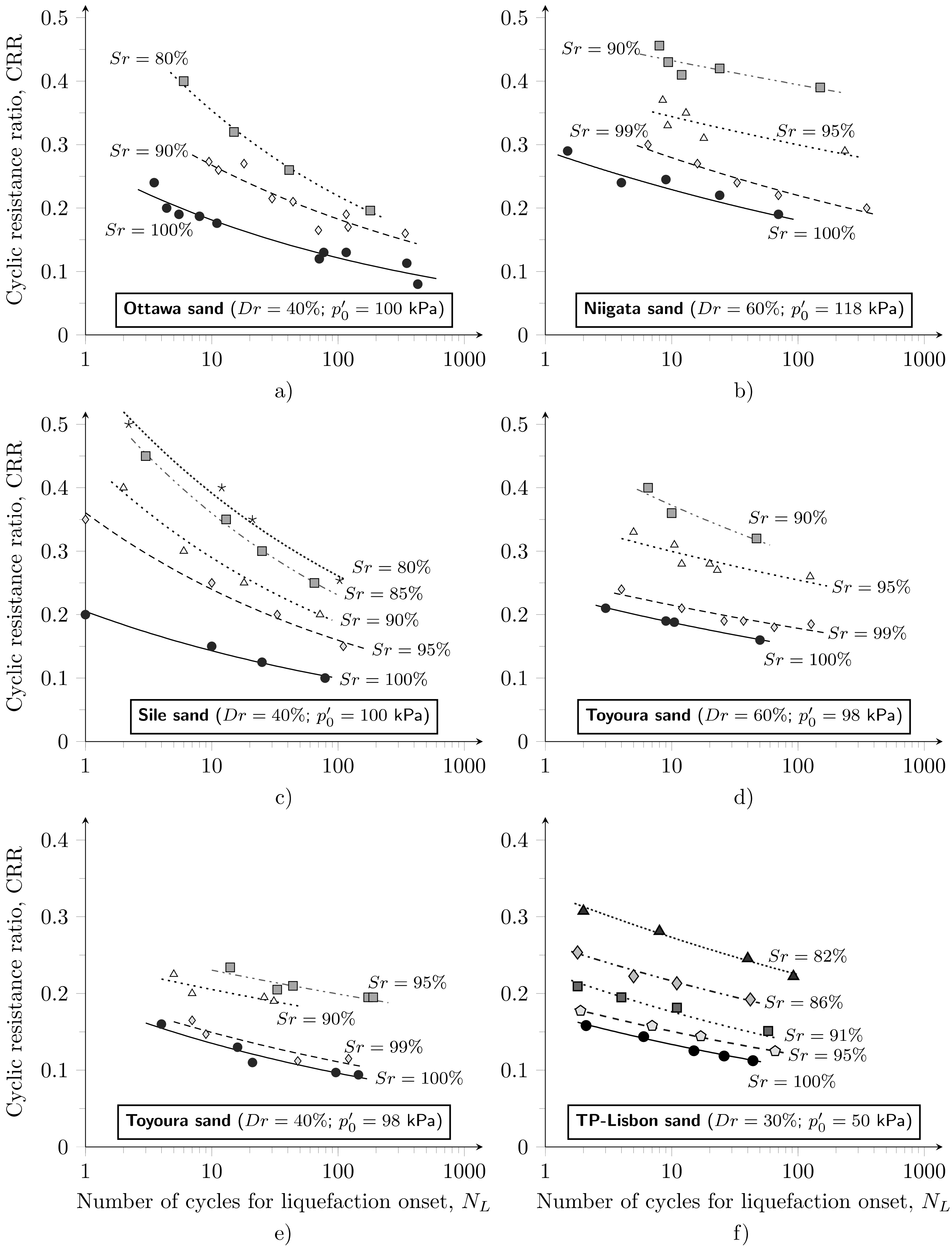

Figure 3. Cyclic resistance curves for different *Sr*: a) Ottawa sand; b) Niigata sand; c) Sile; d) Toyoura sand (*Dr* = 60%); e) Toyoura sand (Dr = 40%); f) TP-Lisbon sand

Table 3 Cyclic resistance curves

Sand	*Sr* (%)	Power law
Ottawa	100	CRR=0.2706$N_L^{-0.174}$
	90	CRR=0.3922$N_L^{-0.166}$
	80	CRR=0.5713$N_L^{-0.208}$
Niigata	100	CRR=0.2899$N_L^{-0.103}$
	99	CRR=0.3553 $N_L^{-0.104}$
	95	CRR=0.3953 $N_L^{-0.061}$
	90	CRR=0.4742 $N_L^{-0.042}$
Sile	100	CRR=0.2899$N_L^{-0.103}$
	95	CRR=0.3553 $N_L^{-0.104}$
	90	CRR=0.3953 $N_L^{-0.061}$
	86	CRR=0.4742 $N_L^{-0.042}$
	80	CRR=0.4742 $N_L^{-0.042}$
Toyoura*	100	CRR=0.1898 $N_L^{-0.148}$
	99	CRR=0.2009 $N_L^{-0.129}$
	95	CRR=0.2411 $N_L^{-0.069}$
	90	CRR=0.2663 $N_L^{-0.062}$
Toyoura+	100	CRR=0.2347 $N_L^{-0.097}$
	99	CRR=0.2592 $N_L^{-0.081}$
	95	CRR=0.3529 $N_L^{-0.071}$
	90	CRR=0.4721 $N_L^{-0.103}$
TP-Lisbon	100	CRR=0.1737 $N_L^{-0.114}$
	95	CRR=0.1896 $N_L^{-0.101}$
	90	CRR=0.2291 $N_L^{-0.114}$
	86	CRR=0.2656 $N_L^{-0.089}$
	81	CRR=0.3321 $N_L^{-0.085}$

*Dr = 40%; +Dr = 60%

The results presented in Figure 3 and Table 3 confirm the evolution of cyclic behaviour for different *Sr*, indicating that the liquefaction resistance increases as *Sr* decreases for the five sands. However, the magnitude of soil improvement is not clearly quantified in this representation. To address this, the results were further interpreted using the normalised cyclic resistance ratio (NCR). The NCR was calculated by computing the ratio between the CRR obtained for 15 cycles in partially saturated conditions (i.e., *Sr* < 100%) and the CRR derived for 15 cycles in fully saturated conditions (i.e., *Sr* = 100%). The CRR for 15 cycles in both partially and fully saturated conditions were obtaining using the power laws for each *Sr* (see Table 3). Figure 4 shows the NCR as a function of *Sr* for all sands.

Experimental data in Figure 4 allow deriving a series of linear relationships to describe the evolution of liquefaction resistance for different *Sr* in all sands. Experimental results reveal that an increase in liquefaction resistance near and above 50% when the *Sr* decreases by 10% (i.e. *Sr* of soil is 90%), which is a good indicator of the effectiveness of induced partial saturation (IPS) techniques for earthquake-induced liquefaction mitigation. Although the evidence of the good performance of IPS, the linear tendencies describing the improvement provided by IPS are not convergent to a common factor. These differences are attributed to testing conditions for each study (i.e., *Dr* and p'_0), which affects the cyclic behaviour of sands due to their influence on the soil stiffness.

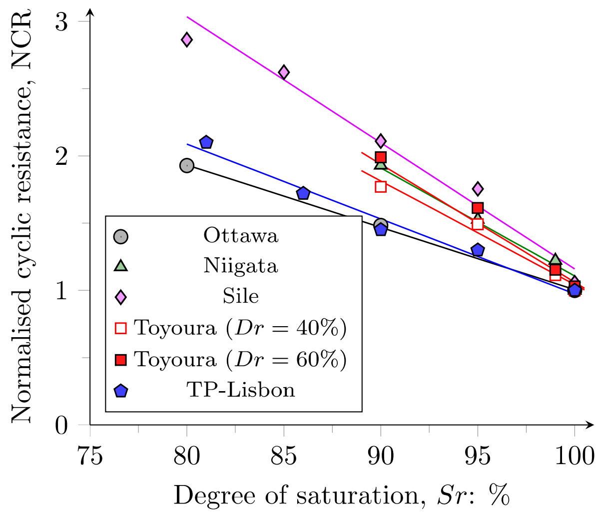

Figure 4. Normalised cyclic resistance as a function of the degree of saturation

Therefore, an alternative approach to describe the improvement in liquefaction resistance is needed. Such an approach should capture the influence of *Sr* on the cyclic behaviour of sands. Astuto et al. (2023) observed that the P-wave velocity (V_P) allows for a suitable quantification of *Sr*, which can be linked to the liquefaction resistance improvement by IPS. The wave-based approach involves a correlation between the NCR as a function of V_P. However, not all data compiled herein included P-wave characterisation. In fact, only the data from Ishihara et al. (1998), Tsukamoto et al. (2002), and Molina-Gómez et al. (2023) reported V_P measurements for the tests conducted in their studies.

Figure 5 presents the results of NCR as a function of V_P. The results revealed a non-linear trend, in which all experimental data fits to 1 for V_P values higher than 1500 m/s (corresponding to *Sr* = 100%). Moreover, this model shows an asymptotic increment in V_P values lower than 500 m/s. The non-linear tendency is fitted in a model estimated from the least squares methods under an R^2 > 0.95, indicated as follows:

$$NCR = 0.96 + \exp^{1.9 - 2.1\ln\left(\frac{V_P}{100} - 1.3\right)} \quad (2)$$

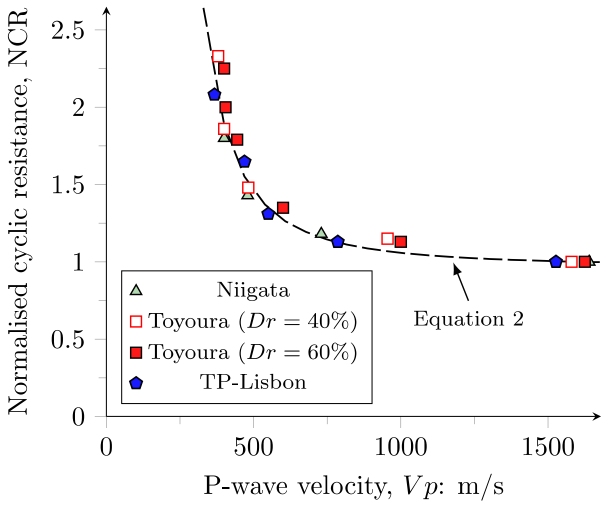

Figure 5. Evolution of normalised cyclic resistance as a function of P-wave velocity

The results in Figure 5 evidence a good adjustment of the experimental data to the model described in Equation 2. This model successfully converges the response observed in the different sands, effectively capturing the effects of *Sr* on liquefaction resistance and cyclic behaviour in the three studied sands. Therefore, the wave-based approach validates the effectiveness of IPS, highlighting the potential of P-wave characterisation in the assessment of cyclic behaviour in fluid saturated granular media.

5. CONCLUSION

This paper has explored the liquefaction resistance and cyclic behaviour in partially saturated sands. Five datasets from well-characterised sands were compiled and analysed herein. A novel parameter, referred to as 'normalised cyclic resistance', was introduced and correlated with the degree of saturation and the P-wave velocity. The non-linear model relating normalised cyclic resistance as a function of P-wave velocity provided a reliable prediction of the effects of degree of saturation in liquefaction resistance. This model is a suitable alternative approach for comparing the liquefaction resistance and cyclic behaviour of sands at different degrees of saturation. However, additional research and validation studies in numerous liquefiable soils and diverse testing conditions are recommended, towards ensuring the applicability and reliability of this wave-based approach.

6. ACKNOWLEDGMENTS

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