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Rate Effects of Model Monopiles in Saturated Sands

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ABSTRACT: Monopiles founded in saturated sand are commonly assumed to exhibit drained behaviour. For offshore wind turbine applications, this may tend towards partially drained behaviour as foundations continue to increase in size and storm events increase in frequency and ferocity with climate change. The PICASO project follows-on from PISA, and aims to increase design efficiency by further characterisation of cyclic loading effects. At 1g model scale, three experimental set-ups aim to further inform on pile behaviour in saturated sands. By varying loading rate, pile size and permeability of the sand, an investigation of a range of drainage conditions, replicable of field scale, is possible. Firstly, dry 14/25 Leighton Buzzard was used to assess pile behaviour without any pore fluid effects. Secondly, oil-saturated 14/25 Leighton Buzzard targets the drained to partially-drained region of behaviour of piles in saturated sand. Thirdly, water-saturated M4 silica flour is used to model the partially-drained to undrained response of model piles in sand. Materials are chosen based on scaling laws that prioritise the alignment of diffusion and dynamic timescales. A short description of the experimental set-up is outlined. Selected results of the three experimental campaigns are shown, highlighting differences in behaviour between dry and saturated sand and sands of different approximate permeabilities. Different pile sizes have been tested to vary drainage length more widely, results of which are partially presented.

Keywords: Monopile, Cyclic, Rate, Saturated sand, PICASO

1 MOTIVATION

Monopiles remain the most popular and well-established foundation type for current offshore wind installations (WindEurope, 2020). Design guidance has been updated recently from the traditional *p-y* approach, through the PISA design method specific to offshore wind turbine monopile foundations.

The PICASO project is a follow-on from the PISA project, of which this research is a part of, with the main aim to further characterise cyclic loading effects on pile performance. This research consists of 1g model testing campaigns in dry and saturated sands to investigate rate effects and cyclic lateral loading behaviour. These experimental results can aid in the calibration of models to predict pile response during loading regimes present in the offshore environment. Through such experimental investigations, the aim is to further optimise design guidance, therefore potentially reducing associated foundation cost and minimising design risk, as turbines and their foundations continue to increase in size. Further background of the PICASO project and its application is outlined by Byrne et al. (2025).

2 EXPERIMENTAL SET-UP

The apparatus used in these investigations was previously developed and commissioned by Wu (2022), and is shown in *Figure 1*.

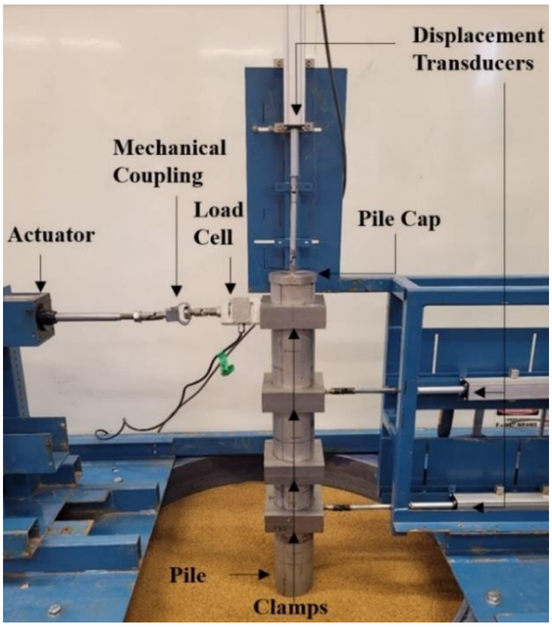

Figure 1 Experimental set-up (Wu, 2022).

Pile movement is monitored through three linear displacement transducers (LDTs), and loading is applied through a linear roller-screw actuator, controlled through LabVIEW.

Sample preparation varied for different test campaigns. Dry sand samples were prepared through air pluviation, using a sand raining device previously developed by Richards (2019), achieving sample relative densities in the range of 55 - 60%. Saturated sand samples required an alternative approach. A novel vibratory table was fabricated to facilitate the preparation of very dense saturated sand samples by vibration, as shown in *Figure 2*. Saturated samples remained submerged for the full test campaign. Dense samples were achieved by using a combination of vacuum applied to the top of the test tank to draw fluid upwards through the sample and vibration to induce compaction. Repeated monotonic tests and a selection of mini-CPTs were completed to validate this procedure.

Figure 2 Vibratory table, used in saturated sand sample preparation.

This method of preparation achieved samples of relative densities in the range 89 - 99% in the case of M4 silica flour. When used for the preparation of the silicone oil saturated 14/25 Leighton Buzzard samples, use of an upward hydraulic gradient helped in loosening the sample, and achieving 65-80% relative densities which were higher but closer to that of the previous dry sand tests.

Materials were chosen based on scaling laws, where diffusion and dynamic timescales are aligned at model scale, to replicate drainage phenomena as they occur at field scale. This approach is well described in Keane and Byrne (2023) and is based on the theoretical work of Wood (2004).

Silicone oil saturated 14/25 Leighton Buzzard was chosen to exhibit behaviour close to the drained to partially-drained response. While M4 silica flour was chosen to target the partially-drained to undrained zone of potential behaviours.

Approximate permeability values, inferred from oedometer tests, at model scale stress-levels are shown in *Table 1*.

Table 1 Granular material approximate permeabilities

	Permeability [m/s]	Relative Density [%]
14/25 Leighton Buzzard (with oil)	3 x 10^{-5}	65-80%
M4 Silica Flour (with water)	3 x 10^{-9}	89-99%

3 RESULTS

3.1 Dry Sand

Dry sand tests in 14/25 Leighton Buzzard demonstrate behaviour comparable to previous model scale test campaigns carried out by Wu (2022), Richards (2019), Abadie (2015) and Leblanc et al. (2010). These tests show trends of piles in sand, omitting the presence of pore fluid and provide a good baseline pile performance, for comparison with the silicone oil saturated tests.

Figure 3 shows the normalised monotonic response at ground-level, using dimensionless groups developed by Leblanc et al. (2010), expressed in terms of pile diameter (*D*) and length (*L*), soil buoyant unit weight, (γ'), and atmospheric pressure, (p_a). The model pile tested was 84 mm diameter, with an aspect ratio of 3.5. This test is a constant-rate test. Wu (2022) investigated rate variation which showed no difference in capacity achieved in monotonic loading. Ultimate rotation (θ_R) was taken to be 2° at ground-level.

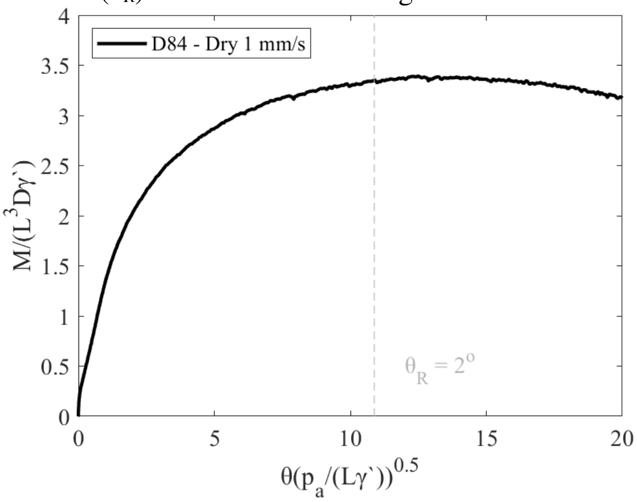

Figure 3 Normalised monotonic response in dry 14/25 Leighton Buzzard.

Cyclic tests with three different amplitudes of loading, 5%, 20% and 30% of ultimate moment M_R, at constant cycling frequency of 0.2 Hz, were carried out and compared in terms of ratcheting or rotation accumulation. This pile rotation trend is shown in *Figure 4*.

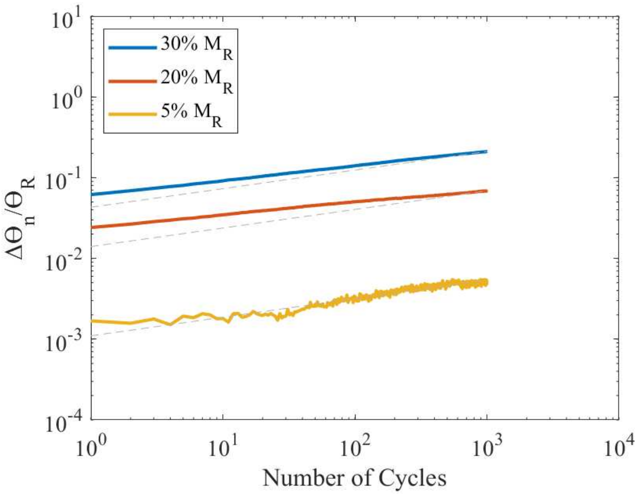

Figure 4 Ratcheting accumulation over 1000 load cycles at 5%, 20% and 30% of M_R. Dashed lines represent power law fit as defined by Leblanc et al. (2010).

The level of ratcheting is greatest for highest load amplitudes. Wu (2022) demonstrated that cyclic frequency does not influence accumulated pile rotation in dry sand. Normalised hysteretic secant stiffness for load cycles in dry sand increases as cycling progresses at the higher load-levels, correlating with observations in previous test campaigns, as shown in *Figure 5*. Secant stiffness is normalised by initial stiffness (k_{max}), defined at 0.003° pile rotation.

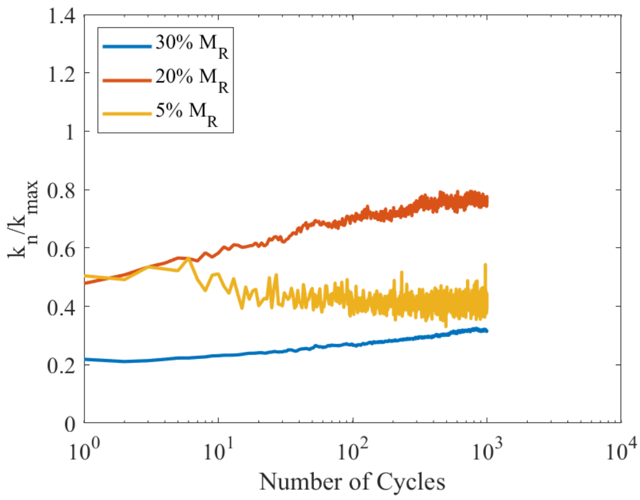

Figure 5 Secant stiffness development over cycling at three load-levels 5%, 20% and 30% of M_R in dry sand.

3.2 Oil-saturated sand

3.2.1 Monotonic tests

100 centi-stoke silicone oil was chosen as the saturant for 14/25 Leighton Buzzard to increase the drainage time for excess pore pressures post-loading. With this scaling approach, the drained to partially drained region of potential loading conditions was modelled. A series of monotonic and cyclic tests on different sized piles was completed - with the smallest dimension of pile presented here, the same as that presented previously for dry sand tests. The pile was monotonically pushed at constant actuation rates of 0.01 and 10 mm/s, with results shown in *Figure 6*. When loaded faster, the pile exhibited a higher ultimate capacity, demonstrating that piles do not exclusively exhibit fully drained behaviour.

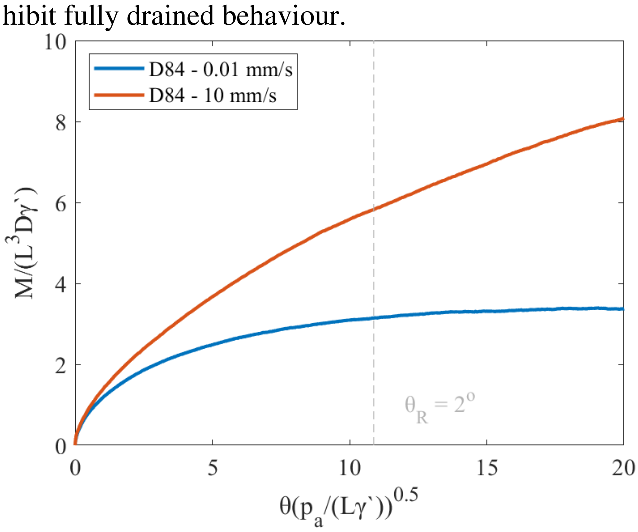

Figure 6 Normalised monotonic tests in oil saturated Leighton Buzzard sand at 0.01 and 10 mm/s loading rates.

3.2.2 Cyclic tests

Cyclic tests were completed at load-levels based on dry sand cyclic tests, at amplitudes of 5%, 20% and 30% of the drained ultimate moment, M_R.

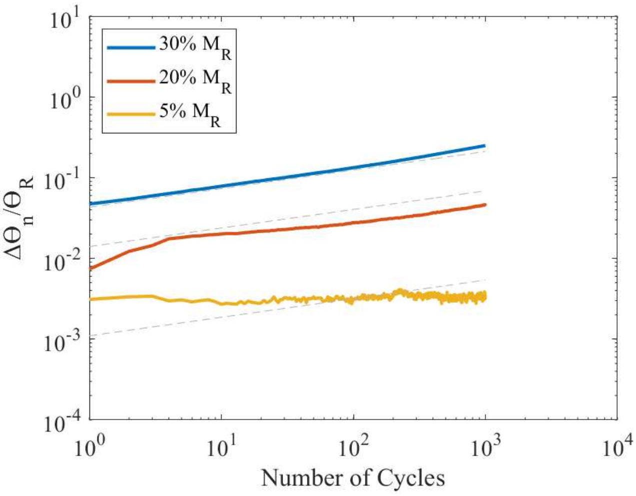

Figure 7 Pile rotation accumulation at three cyclic load levels 5%, 20% and 30% of M_R. Dashed lines represent equivalent tests in dry sand.

Figure 7 graphs the accumulated pile rotation in oil-saturated sand at these three load-levels, providing a partially drained comparison to the dry sand trends in *Figure 4* previously. Relative densities achieved for the oil-saturated tests (65 – 80%) are higher than that for the dry tests (55 - 60%) due to different sample preparation methods used. Pile ratcheting trends in oil-saturated Leighton Buzzard appear consistent with that observed in the dry material. It is noted that, at low load levels, accumulated pile rotation increases only slightly as cycling progresses. At higher amplitudes, the rate of ratcheting appears to follows the trend from the dry tests rather well, considering small differences in sample densities.

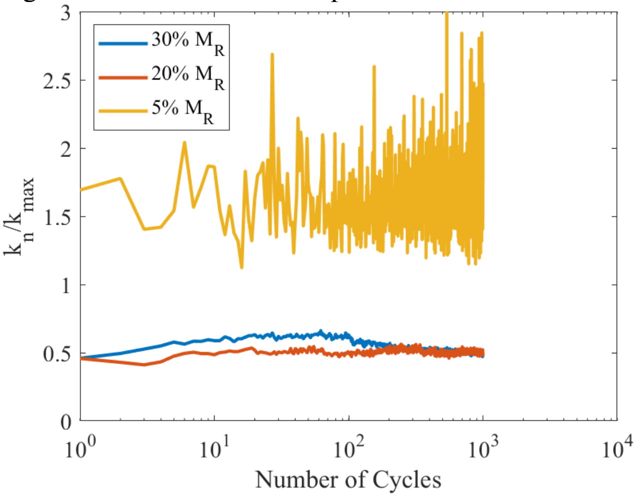

Figure 8 Secant stiffness development over cycling at three load levels 5%, 20% and 30% of M_R.

Figure 8 shows the variation in secant stiffness at different load-levels in oil-saturated Leighton Buzzard. Secant stiffness values remain widely consistent over 1000 load cycles at all load levels. While a small amount of softening is observed at the 30% level, the magnitude of softening does not surpass that of the initial cycles. This is comparable to dry sand trends in Figure 5, where stronger hardening is observed.

3.3 Water-saturated silica flour

3.3.1 Monotonic tests

A similar campaign of tests were carried out on M4 silica flour submerged in water. Kelly et al. (2006) used silica flour for modelling suction caisson behaviour at model scale. *Figure 9* shows a series of constant-rate monotonic push tests, at ground-level displacement rates of 0.05, 1 and 5 mm/s. These tests were carried out on a reduced pile size ($D = 50mm$), installed to an aspect ratio of 3.5.

Faster loading rates induce much higher lateral pile capacity, showing similar behaviour to the oil-saturated monotonic tests. However, the shape of the failure curve deviates from that observed in previous test campaigns. Pile resistance to movement at higher rates increases rapidly for piles in silica flour, and there appears to be no limiting capacity. These saturated tests target the partially-drained to undrained region, the faster rate monotonic responses approach this *undrained* loading condition at model scale. Larger pile sizes were also tested at high rates which showed an even stronger response and correlation with loading rate, however they are not reported here.

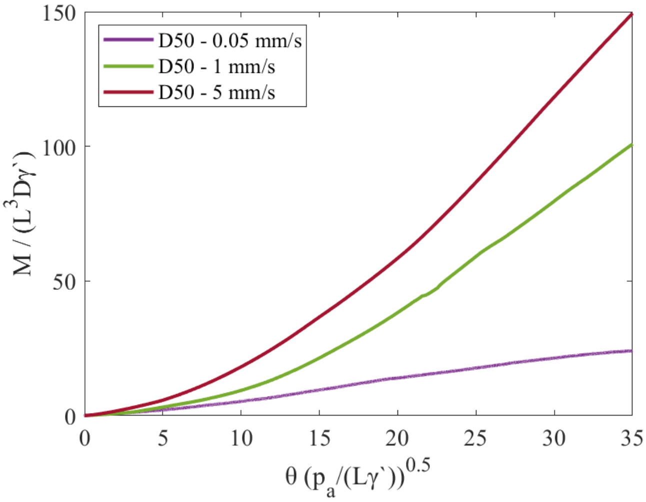

Figure 9 Monotonic tests in M4 silica flour and water at loading rates of 0.05, 1 and 5mm/s.

3.3.2 Cyclic Tests

Three different cyclic loading amplitudes were tested, 11%, 20% and 35% of the ultimate moment (M_R), determined from the slowest monotonic test. The frequency of cyclic loading patterns was 0.2 Hz.

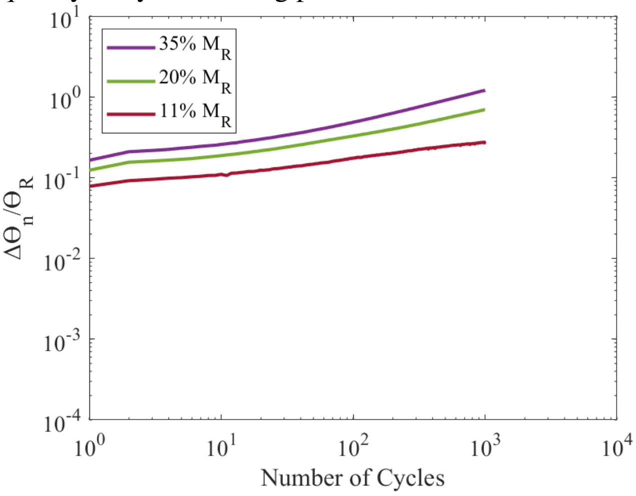

Figure 10 Ratcheting in M4 silica flour for three cyclic load levels, 11%, 20% and 35% of M_R.

Ratcheting rates in water-saturated silica flour, shown in *Figure 10*, are higher than that observed in both previous investigations, though follow a consistent pattern. This indicates that there are no material differences to behaviour, although these cyclic tests are at rates closer to undrained than drained.

Cycle secant stiffness varies in silica flour tests, as in *Figure 11*. The lowest amplitude cycles, of 11% M_R, demonstrate comparable trends to that seen in dry sand of increasing secant stiffness with cycle number. The magnitude of stiffness relative to the initial loading stiffness (k_{max}) is substantially higher in the case of silica flour than in previous test campaigns. Upon installation of the pile by driving, potential weakening of the flour surrounding the pile results in low observed initial stiffness in all tests. Cycling at higher load magnitudes results in broadly constant stiffness across the 1000 cycles, with some variation with cycle number.

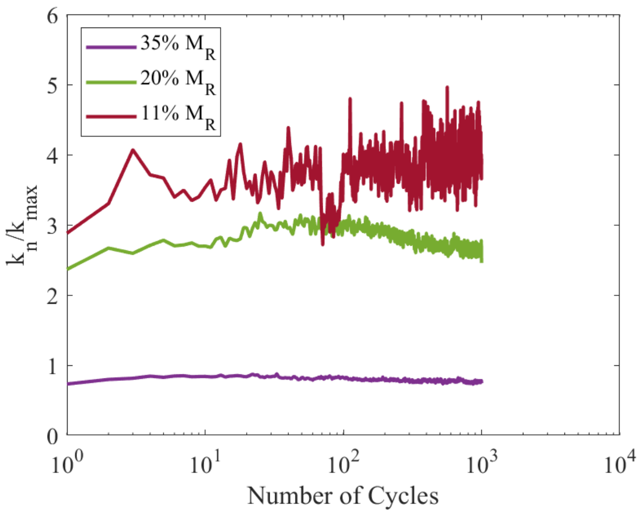

Figure 11 Secant stiffness development with cycling at three load levels 11%, 20% and 35% of M_R.

An investigation into cyclic loading frequency effects is supplementary to the previous silica flour cyclic tests. *Figure 12* shows that strain accumulated due to cyclic loading are not dependent on cycling frequency, but driven more so by cyclic load amplitude.

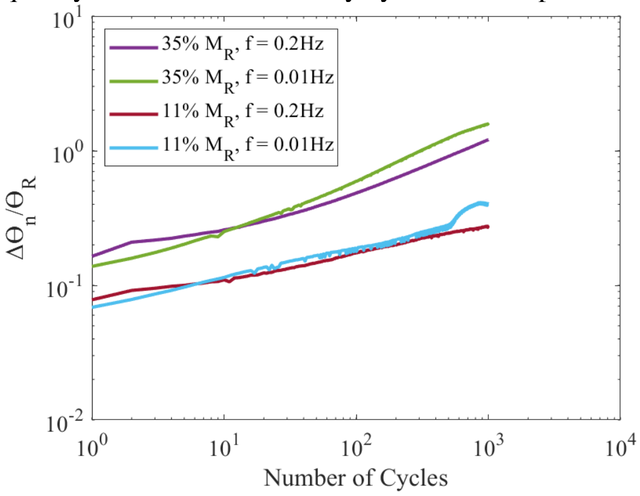

Figure 12 Pile rotation accumulation for cycles of varying frequencies of 0.01Hz and 0.2Hz at two load levels 11% and 35% of M_R.

4 MONOTONIC RESULTS NON-DIMENSIONALISED

To summarise the non-dimensional rate effects for monotonic loading, *Figure 13* shows the relationship between capacity and normalised loading rate for both saturated sand set-ups.

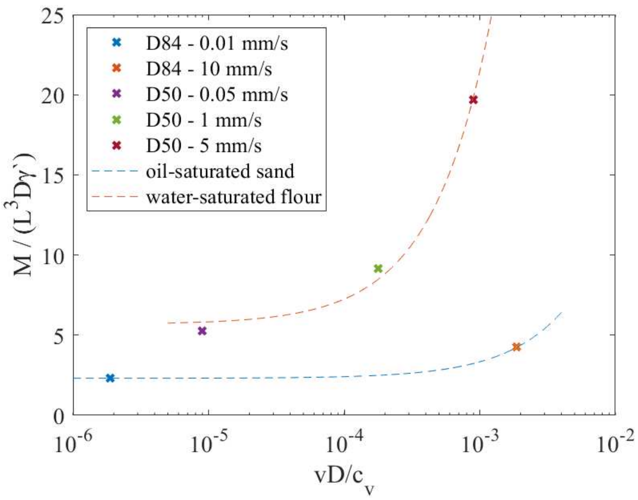

Figure 13 Dimensionless summary of pile ultimate moment for varying loading rate v.

The magnitude of increased capacity is greater in the silica flour set-up as it exhibits partially-drained to undrained pile behaviour, while the oil-saturated sand demonstrates drained to partially-drained trends. Pile loading rate is defined by v, pile diameter (assumed equivalent to drainage length) is denoted D and coefficient of consolidation is represented by c_v. Further population of this parameter space will be important to quantify the impact of rate on design.

5 CONCLUSIONS

The purpose of this investigation is to explore the impact of drainage in sands, as this is not particularly captured in current design guidance. Three test set-ups are reported:

1. Dry 14/25 Leighton Buzzard
2. 14/25 Leighton Buzzard saturated with 100cS silicone oil
3. M4 silica flour saturated with water

Firstly, the dry sand tests were completed to demonstrate baseline response for model piles in dry material, omitting the potential influence of excess pore pressures. The outcomes of this investigation, compare closely with Wu (2022) and Richards (2019), show increase in rotation accumulation and secant stiffness as cycling progressed at all three load-levels.

Oil-saturated 14/25 Leighton Buzzard demonstrated drained behaviour at lower monotonic loading rates and low cyclic load amplitudes. Upon increasing push-over speed or cyclic load amplitude slightly different behaviour emerged. In the case of monotonic tests, higher lateral capacity was observed for faster loaded piles. Cycling at higher load magnitudes generated larger pile movements when compared to the dry sand tests, and demonstrated relatively constant hysteretic secant stiffness across the applied cycles.

In the silica flour tests, with much reduced relative permeability compared to the oil-saturated Leighton Buzzard sand tests, the increased loading rates demonstrated a strong enhancing influence on pile ultimate capacity. At low cyclic load levels, cycling frequency effects were not evident.

This 1g model test campaign aims to accompany the data obtained as part of the PICASO project, including a medium-scale field test campaign and element testing. The data collected in this investigation will be used for calibration purposes and theoretical development to enable consideration of partial drainage phonomena at design stage, previously unconsidered for piles in sand.

AUTHOR CONTRIBUTION STATEMENT

Rachel Keane: Data curation, Investigation, Project Administration, Formal Analysis, Software, Validation, Writing- Original draft.
Byron W. Byrne: Supervision, Funding acquisition, Writing- Reviewing and Editing.

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