Drainage in saturated sands surrounding offshore monopiles

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ABSTRACT: Wind turbine foundations, particularly monopile foundations, have undergone significant enhancements in design efficiency in recent years, underpinned by investigations such as the PISA project. As turbines increase in size, foundation optimisation becomes increasingly important so that wind energy continues to be a cost-effective renewable energy technology. Rate effects are felt to be an important element of monopile behaviour but there is no guidance to quantify possible impact on design. A 1g model testing campaign was undertaken to identify the effect of partial drainage during rapid loading events on model monopile foundations installed in saturated sands. Part of the investigation involved varying the pile size, with a total of five different model pile diameters used in two different permeability sands. As conservation of all full scale parameters at laboratory scale is not usually possible the dissipation of excess pore pressure was prioritised. The scaling approaches are described in detail. A series of monotonic push-over tests and cyclic loading tests were completed where loading rate, and cyclic loading amplitude, frequency and degree of asymmetry were varied on different model piles. A selection of results are presented. This work forms part of a larger joint industrial project between Oxford and Ørsted- the PICASO project, which aims to further characterise and update design guidance for cyclic lateral loading of offshore monopiles.

1 INTRODUCTION

Offshore wind foundations are subjected to tens of millions of environmental and operational load cycles throughout their lifetime. As over conservatism in design reduces, to promote further investment and continued support of renewables in the energy mix, it is necessary to refine many aspects of existing pile design guidance as next generation monopiles increase in size and cost.

Cyclic loading needs more detailed consideration to ensure design is appropriate. The PICASO project was formed to further investigate cyclic loading effects in both sands and clays, through physical modelling alongside theoretical / numerical work. Building on the success of the PISA project (Burd et al., 2020; Byrne et al., 2020), to reduce conservatism in design that could be implemented by engineers in practice, the PICASO project also aims to further refine guidance for offshore monopiles (Byrne et al., 2025).

The impact that partially drained conditions have on the response under operational cyclic load levels and ultimate capacity requires careful examination. As the phenomena of partially drained loading conditions in granular materials is investigated, its consideration at design stage may become necessary to maintain efficiency, particularly as offshore turbines continue to increase in size (Li et al., 2019).

2 EXPERIMENTAL SET-UPS

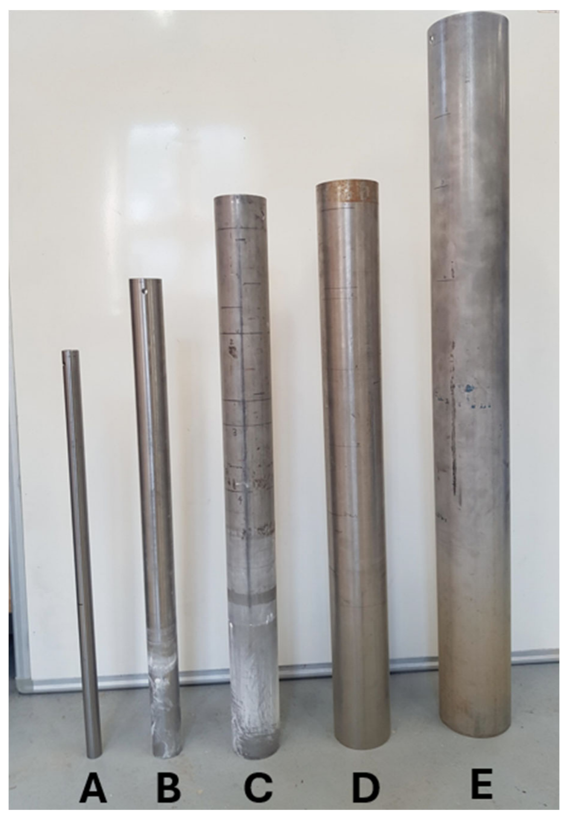

Figure 1. Monopile geometries tested.

In this investigation, 1g model testing of different model pile geometries is completed in two independent soils. This section describes the experimental rig as well as the sample preparation procedure. Figure 1 shows the range of model piles used, where model pile A has a diameter of 25 mm and model pile E has a diameter of 129 mm.

2.1 Instrumentation and test set-up

Wu developed an experimental set-up to monitor and control lateral pile loading tests at 1g model scale (Wu et al., 2020; Wu et al., 2022). Figure 2 shows the set-up where the model pile movement is measured by three linear displacement transducers (LDTs), two parallel to the horizontal at two different heights above the soil and another vertical fixed directly above the pile's starting position.

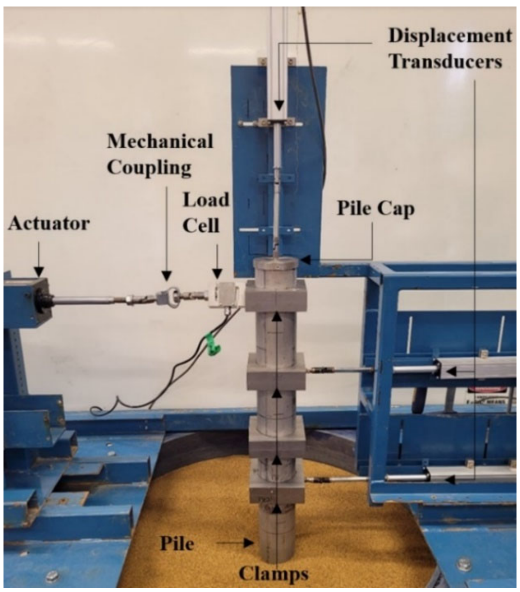

Figure 2. Experimental apparatus for lateral loading of piles, developed by Wu (2022).

An electric actuator, load cell and control feedback system is used to execute the test. For tests with oil saturated sand pore pressure transducers (PPTs) are placed in the soil to monitor the drainage of excess pore pressures during lateral pile movement in both monotonic and cyclic tests.

2.2 Sample preparation method

Two alternative saturated sand samples were used during this test campaign – one oil-saturated 14/25 Leighton Buzzard sand and the other water-saturated M4 Silica Flour.

The process of preparation of both samples involves a reconstitution method, by means of a combination of vibration (by a shake table), and application of a vacuum to the top of the samples (to help remove air and to promote upward flow of the fluid through the sample). Figure 3 shows the test tank placed on a shake table for the purposes of sample reconstitution.

Figure 3. Sample preparation for saturated sand by means of reconstitution.

Sample relative densities and approximate permeabilities achieved for both 1g model scale set-ups are given in Table 1, which are calculated globally and by oedometer tests respectively.

Table 1. 1g soil parameters, relative density (D_r) and permeability (k).

	Dry YLB sand	Oil-saturated YLB sand	Water-saturated M4 flour
D_r [%]	55	65 – 80	99
k [mm/s]	n/a	3×10^{-5}	3×10^{-9}

Other campaigns using silica flour include Kelly et al. (2006), in model scale investigations of suction caissons. Further characterisation of M4 grade silica flour is included in Keane (2025).

3 SCALING ACHIEVEMENTS

Scaling laws for 1g laboratory tests that mimic larger scale problems are central to the interpretation and validity of results. As there are two alternative 1g set-ups, both methods of scaling are discussed in terms of soil parameters maintained between scales and those that are unconserved when carrying out tests at reduced scale on the laboratory floor.

Though results can be extrapolated to an equivalent prototype case, test results are presented only in model scale. The laboratory floor experiments attempt to recreate phenomena that exist at full-scale, though quantitively, model and equivalent prototype soils may not scale absolutely.

To demonstrate this, pile size effects are modelled here by comparing varied rate monotonic pushover tests for different model pile sizes testing using the same method in the same soils. Trends are deduced from the set-up by comparison of model test results, rather than translating to equivalent prototype scale.

In general terms, scaling laws outlined by Wood (2004) are used for the 1g model testing set-ups. The priority in both soil types used is to prioritise the alignment of diffusion and dynamic timescales over other soil parameters. Through this scaling approach, partial drainage phenomena that occur at prototype scale can be modelled in the lab, though compromises on other quantities warrant consideration when interpreting results.

3.1 Dimensionless groups

Laterally loaded rigid piles have been previously investigated by Leblanc et al. (2010). The development of dimensionless groups to capture the non-dimensional pile response, contained in Leblanc, are defined in Table 2, where *D* and *L* are pile diameter and length respectively, effective unit weight is defined by γ' and p_a is atmospheric pressure.

These groups form the basis of this study. They account for soil saturation (importantly with different pore fluids) by the use of effective unit weight in the expressions. However, potential loading speed effects due to partial drainage phenomena are not accounted for by these dimensionless quantities.

An additional dimensionless group is needed to include effects of partial drainage in sands. Ideally, this dimensionless quantity incorporates the pile size, soil permeability and the speed of load application. Pile diameter (*D*), loading speed (v) and coefficient of consolidation (c_v) are used as the inputs to the new dimensionless group, defined in Equation 1.

Table 2. Dimensionless groups for rigid, laterally loaded piles in sand (Leblanc et al., 2010).

Dimensional quantity	Dimensionless group
Overturning Moment, M	$\frac{M}{DL^3\gamma'}$
Horizontal load, H	$\frac{H}{DL^2\gamma'}$
Vertical load, V	$\frac{V}{DL^2\gamma'}$
Load eccentricity, e	$\frac{M}{HL}$
Pile rotation, θ	$\theta\sqrt{\frac{p_a}{L\gamma'}}$
Aspect ratio, η	$\frac{L}{D}$

$$\frac{vD}{c_v} \tag{1}$$

Though there will be some vertical drainage, pile length is not included in the expression as the dominant direction of lateral loading causes radial drainage to be the more critical drainage pathway.

By incorporating this dimensionless quantity, trends in model pile behaviour can be deduced, relating pile drainage to the previously defined dimensionless groups in Table 2. Examples of such correlations are reported by Keane and Byrne (2025).

3.2 General scaling laws

At 1g, scaling of soil behaviour, particularly saturated sands, require careful consideration. Wood developed scaling laws for model set-ups at 1g and at ng, which form the basis of the scaling approach used in both model soils described in this testing campaign. Table 3 outlines scaling laws of different quantities which applies to both oil-saturated Leighton Buzzard sand and water-saturated silica flour, as defined by Wood (2004).

Where n_x is a dimensionless quantity that captures the scale effect, of quantity *x,* between model and prototype scales.

Table 3. General scaling laws for saturated sands at 1g, (Wood, 2004).

Quantitiy	Scaling Law
Length, l	$n_l = \frac{L_{model}}{L_{prototype}} = \frac{1}{n}$
Stress, σ	$n_\sigma = \frac{1}{n}$
Shear stiffness, G	$n_G = \frac{G_{model}}{G_{prototype}} \propto \sigma^\alpha$
Unit Weight, γ'	$n_{\gamma'} = \frac{\gamma'_m}{\gamma'_p}$
Permeability, k	$n_k = \frac{n_{\rho f} n_g}{n_\mu}$
Coefficient of consolidation, c_v	$n_{cv} = \frac{n_k}{n_{mv} n_{\rho f} n_g}$
Diffusion Time, t_{diff}	$T_v = \frac{c_v t_{diff}}{D^2}$
	$n_{t,diff} = \frac{n_\mu n_l^2}{n_G}$
Dynamic Time, t_{dyn}	$n_{t,dyn} = n_l \sqrt{\frac{n_\rho}{n_G}}$

3.2.1 Pile geometry

Various pile geometries are tested as part of this test campaign. Scaling factors for length (n_l), based on the NREL 15 MW reference turbine range from 0.0025 - 0.0129, based on a 10 m prototype pile diameter.

The level of embedment is kept constant for tests shown here, at *3.5 D*, in-line with rigid piles being installed offshore today.

Height of load application is not necessarily proportional to either wind or wave loading heights but is kept constant across tests of the same pile size.

3.2.2 Soil

Both 1g soils are chosen to prioritise the alignment of diffusion and dynamic timescales at 1g scale. This is achieved by slowing the drainage of the pore fluid through sand samples.

Diffusion and dynamic time generalised scaling laws, defined in Table 3, form the basis of the alignment of the two quantities. Diffusion time is dimensionally defined by Terzaghi by the dimensionless time factor, T_v. Dynamic time is deduced from the conservation of energy law, where kinetic and potential energies can be equated. Table 4 outlines the quantification of both timescales and their correlation at 1g model scale. Wood (2004) quotes a typical value of 0.5 for α of sands (the interdependence between stress and strain).

Table 4. Correlation of diffusion and dynamic timescales at 1g model scale.

Diffusion timescale	Dynamic timescale
$T_v = \frac{c_v t}{H^2}$	$E_{potential} = E_{kinetic}$
$n_{t,diff} = \frac{n_\mu n_l^2}{n_G}$	$n_{t,dyn} = n_l \sqrt{\frac{n_\rho}{n_G}}$
$n_{t,diff} = \frac{1}{n^{2-\alpha}}$	$n_{t,dyn} = n^{\frac{\alpha}{2}-1}$
$if\ \alpha = 0.5\ (typical\ for\ sands)$	
$n_{t,diff} = n^{-1.5}$	$n_{t,dyn} = n^{-0.75}$

From the comparison of diffusion and dynamic time scaling laws, the necessity to alter the 1g model set-up is evident – either by increasing the drainage time, or by reducing the dynamic time. Typically, slowing the drainage of excess pore pressures is the approach taken, which is adopted in two alternative ways in each of the 1g set-ups for this campaign.

In oil-saturated 14/25 Leighton Buzzard sand, slower drainage times (diffusion) are made possible through the use of silicone oil, which has a viscosity of 100 centi-Stoke. Due to its higher viscosity, any excess pore pressures that develop in the soil dissipate at a more realistic rate, relative to the dynamic timescale.

In water-saturated M4 silica flour, the slowing of drainage time is achieved through the use of a finer particle granular material - reducing the intrinsic permeability. Water is used as the fluid in this case.

Both set-ups target different ranges of potential excess pore pressure dissipation post-loading. In the case of oil-saturated sand, a drained to partially drained range of behaviours is modelled on the laboratory floor. Whereas the water-saturated silica flour series of tests achieve loading conditions in the partially drained to undrained region of potential loading conditions.

3.2.3 Loading characteristics

Loading frequency is an important input for the cyclic loading tests. The maximum achievable loading speed of the rig was 0.5 Hz, lower than desirable to maintain similitude between model and prototype scales.

Cyclic loading magnitudes are based on pile ultimate capacity, determined by first performing an independent monotonic push-over test per model pile size.

Testing of different degrees of uni-directional load reversal is undertaken as part of these tests. Further results are presented in Keane (2025).

3.3 Limitations

At 1g model scale it is not possible to maintain full similitude between the field and laboratory scale soils, and as a result compromises are inevitable.

3.3.1 Stress level

When carrying out 1g experiments, stress-level remains unconserved. As the coefficient of consolidation is dependent on stress-level, it is central to this investigation.

3.3.2 Strength

Soil strength is not fully conserved in either saturated sand model set-up. At 1g scale, reduced sample relative density is needed to maintain equivalent friction angles to the prototype soil. Due to the sample preparation method used, where samples are reconstituted by vibration, medium dense to dense saturated sand test samples are produced. This was an appropriate approach for the modelling of drainage and permeabilty. It strongly affects the silica flour results and, to a much lesser extent, the oil-saturated tests.

3.3.3 Dilatancy

Dilation is also not fully conserved between scales, which may have an effect on the magnitude of dilation and negative excess pore pressures created in both set-ups – but the phonomena observed are deemed valid based on the realistic scaling achieved regarding diffusion time.

To quantify the effect of not conserving dilation, calculations of dilatancy index are provided in Table 5 – for oil-saturated Leighton Buzzard sand, water-saturated silica flour and a typical prototype problem. Equation 2 defines Bolton‘s law relating dilatancy index (I_R) to relative density (D_r) and mean effective stress (p') (Bolton, 1986).

$$I_R = D_r(10 - \ln(p')) - 1 \tag{2}$$

However, Chakraborty and Salgado (2010) demonstrates that low confinement pressures (p'< 150 kPa), show little deviations in sand dilatancy, which lessens the impact that lower confinement pressures have on results reported in these 1g campaigns.

Table 5. Dilatancy Index calculations of model and prototype soils.

	Oil & LB	Water & M4	Prototype (typical)
D_r [%]	80	99	60 - 80
γ' [$\frac{kN}{m3}$]	11.6	10.1	9.5
$\frac{L}{2}$ [m]	$\frac{0.294}{2}$	$\frac{0.175}{2}$	$\frac{35}{2}$
p' at $\frac{L}{2}$ [$\frac{kN}{m3}$]	1.71	0.88	166.3
I_R [-]	6.6	9.0	1.9 – 2.9

3.3.4 Loading frequency

A default loading frequency of 0.2 Hz at model scale is used for the majority of cyclic loading tests undertaken. This cycling frequency is chosen based on the rig capabilities. It is important that cycling frequency is increased at model scale to replicate the dynamic timescale of the prototype problem. The frequency achieved in these tests is slightly slow for the achievement of full similitude, limited by the use of electric actuators in the control feed-back system.

4 MONOTONIC TEST RESULTS

A series of different speed push-over tests are carried out on both oil-saturated 14/25 Leighton Buzzard sand and water-saturated M4 silica flour.

4.1 Oil-saturated sand

As part of the monotonic investigation, pile geometries are varied. Table 6 describes the different pile sizes tested and equivalent pile sizes tested in a baseline dry sand model set-up.

Table 6. Pile test dimensions in oil-saturated Leighton Buzzard sand.

	PILE C (D84)
D (mm)	84
L (mm)	294
e (mm)	573
L/D (-)	3.5

By using piles of increasing diameters in the same soil makes it easier to assess the influence that foundation geometry has on pile behaviour in partially drained conditions. All model piles were tested at aspect ratios of 3.5 – for larger diameters, the level of embedment is also proportionally higher.

In oil-saturated sand, there is a clear dependency on loading speed. Wu (2022) previously proved, using the same rig and model pile size C, that loading speed had negligible effect on pile response in dry 14/25 Leighton Buzzard sand. Therefore, the presence of the oil impacts pile behaviour.

Figure 4 plots normalised pile moment against pile rotation, to compare dry baseline tests with equivalent oil-saturated pushover tests for pile C. The quantities in the dimensionless groups are previously defined in Table 2 and by Leblanc et al. (2010).

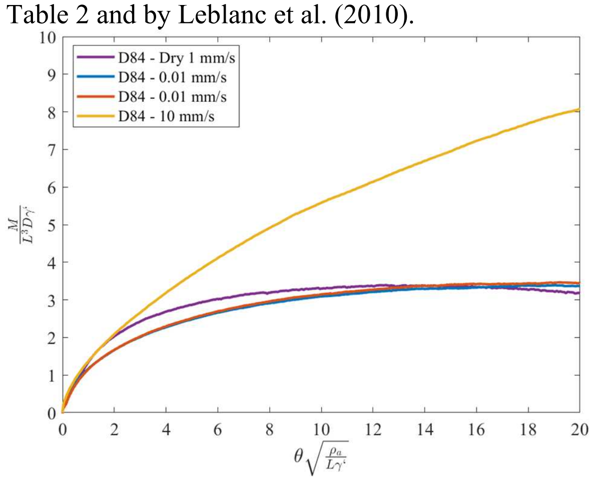

Figure 4. Dimensionless monotonic test results on Pile C.

Pile C demonstrates a response in the saturated material (at slow speeds) that is comparable to that in the dry sand, particularly at ultimate limit state. This result provides evidence that the difference in effective soil unit weights (γ') is the only differing parameter in the dimensionless groups between saturated and dry set-ups.

4.2 Water-saturated flour

M4 silica flour submerged in water is used in an independent test program completed to investigate the effects of pile size under partially drained loading conditions. As the permeability of the soil is much lower than that of the oil-saturated sand set-up, pile behaviour is expected to be capable of approaching the undrained limit of potential conditions. Table 7 defines the model pile geometry tested as part of this test campaign. Smaller model piles are tested in this set-up due to the lower permeability of water-saturated silica flour.

Table 7. Pile test dimensions in water-saturated silica flour.

	PILE A (D25)
D (mm)	25
L (mm)	88
e (mm)	390
L/D (-)	3.5

Figure 5 shows the pile response in water-saturated silica flour for the model pile geometry described.

A clear rate dependent behaviour is evident from this series of tests carried out on piles in water-saturated silica flour. These results are consistent with those in oil-saturated sand, as increased speed of loading mobilises an enhanced pile capacity. The trend in pile capacity with accumulated strain during the push-over seems to increase indefinitely in the case of all flour tests presented, with the exception of the slowest test carried out on Pile A, separately plotted in Figure 6.

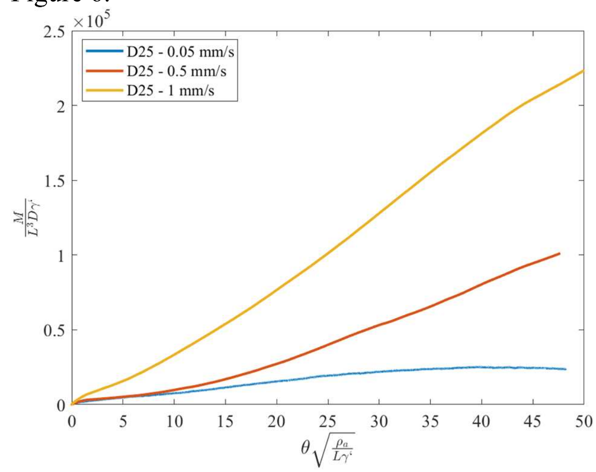

Figure 5. Monotonic response in water-saturated silica flour on Pile A.

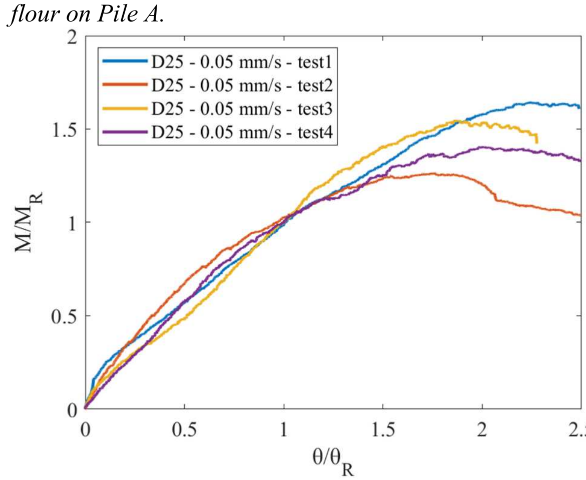

Figure 6. Monotonic response of Pile A at 0.05 mm/s.

5 DRAINAGE DURING CYCLIC LOADING IN OIL-SATURATED SAND

As cyclic loading is the dominant loading regime in the offshore environment, modelling of its effects may potentially inform more detailed design guidance. In sands, model monotonic tests have shown that partially drained conditions are present in the model soils and these have a significant impact on ultimate pile capacity. A test program investigating cyclic loading was completed in both model soils previously described. Cyclic regimes of varying load amplitude were executed. Pore pressure transducers (PPTs) were positioned in the oil-saturated sand set-up to monitor the develpment of exess pore pressures in the surrounding soil. Figure 7 and Figure 8 show four model tests in the oil-saturated sand where loading amplitude is varied. Loading amplitude is based on the drained backbone curve, carried out at 0.05 mm/s on Pile C. Load cycles of 30, 20, 10 and 5% are applied to model pile C (in separate tests).

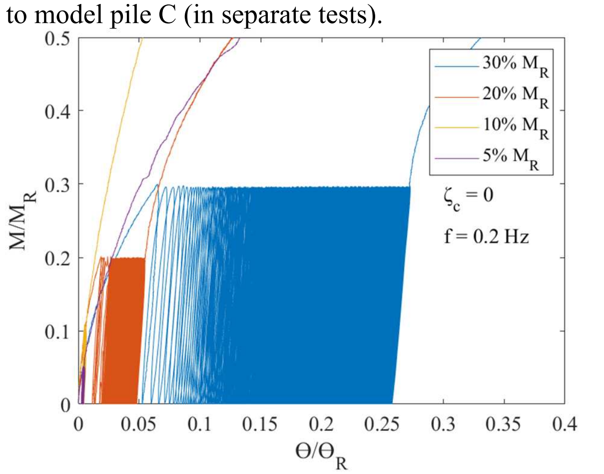

Figure 7. Cyclic loading tests in oil-saturated sand of different load magnitudes for 1,000 load cycles at 0.2 Hz and one-way.

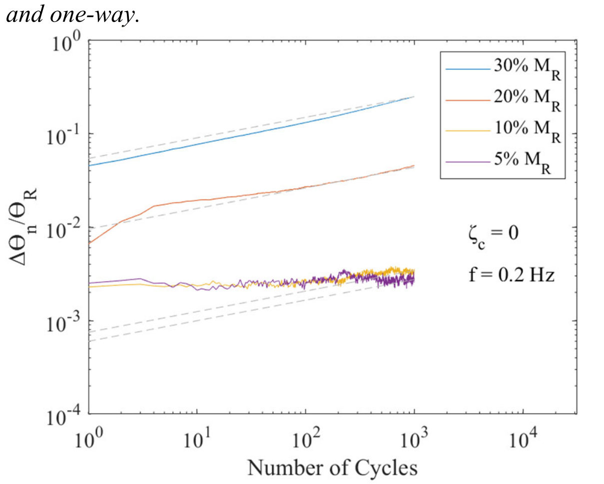

Figure 8. Ratcheting trends of cyclic tests of 30, 20, 10 and 5% cyclic load magnitudes.

The largest pile movements are observed at higher cyclic load amplitudes, consistent with observations from dry sand testing (Richards, 2019; Wu, 2022). Figure 8, showing the strain accumulation over 1000 cycles, demonstrates similar trends to that observed in equivalent dry sand tests of the same pile. This supports monotonic results in oil-saturated sand, where the role of excess negative pore pressures becomes influential at large strains. Tests were carried out at 0.2 Hz, slightly slower than desirable from a scaling perspective. Post-cyclic pile capacity was also tested but not reported here.

Figure 9 and Figure 10 plot the PPT readings for the first 10 cycles of the lowest and highest load amplitude tests reported above in oil-saturated sand. No significant variation in pore pressures is noted at the lower amplitude of 5%. At 30% cyclic loading magnitude, there is an evident cyclic trend in values. This cyclic pattern seems to follow the corresponding load path being applied to the pile. There is no emerging accumulation of excess pore pressures in either case for this first part of the tests.

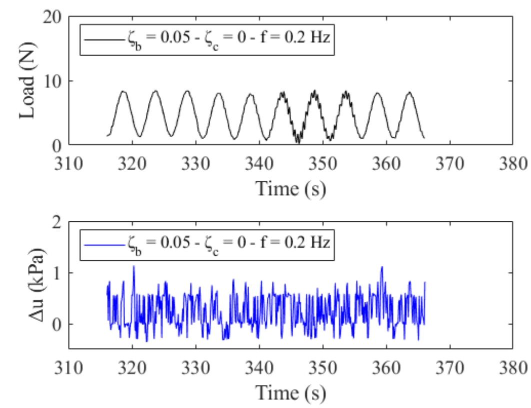

Figure 9. Pore pressure readings at 5% cyclic load magnitude test.

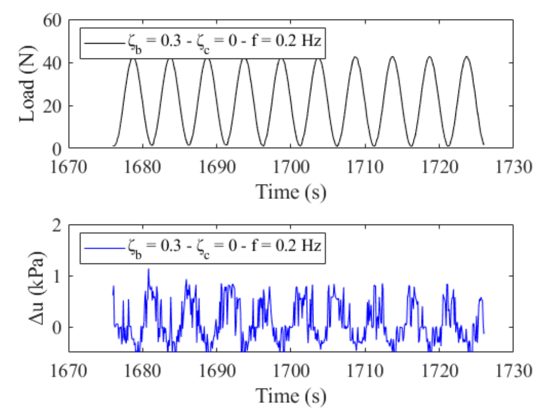

Figure 10. Pore pressure readings at 30% cyclic load magnitude test.

6 CONCLUSIONS

As part of this broad 1g model testing campaign, two main themes emerge – drainage related rate effects during pile push-over and cyclic loading and the absence of the accumulation of excess pore pressures.

- Rate effects are evident in the monotonic phase of testing in both saturated sand set-ups. Increased loading speed enhances pile capacity in both oil-saturated sand and water-saturated silica flour. In silica flour, where permeability is very low, no limiting rate was encountered as undrained conditions are approached. Scaling considerations are also central to the interpretation of these test results where strength is not fully conserved in either model soil at 1g scale.

- Cyclic Loading has been more widely investigated in terms of loading magnitude, frequency and degree of load reversal in uni-directional space. In this paper, a series of different cyclic amplitude tests are reported, generally showing very similar trends to equivalent tests in dry sand. Pore pressure transducers, embedded in the sand, show no specific change in excess pore pressure development during cycling at low cyclic load levels. At higher load levels a cyclic variation in excess pore pressure is recorded, that seems to follow the load command closely for the first 10 cycles of loading.

Overall, the enhancement of pile capacity due to loading speed and the similarity in the saturated sand cyclic loading tests to that previously reported in dry sand investigations are two major outcomes of these 1g experimental campaigns.

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