A Discrete Element Method Centrifuge Model of Monopile under Cyclic Lateral Loads

Nuo Duan, Yi Pik Cheng

***Abstract*—**This paper presents the data of a series of two-dimensional Discrete Element Method (DEM) simulations of a large-diameter rigid monopile subjected to cyclic loading under a high gravitational force. At present, monopile foundations are widely used to support the tall and heavy wind turbines, which are also subjected to significant from wind and wave actions. A safe design must address issues such as rotations and changes in soil stiffness subject to these loadings conditions. Design guidance on the issue is limited, so are the availability of laboratory and field test data. The interpretation of these results in sand, such as the relation between loading and displacement, relies mainly on empirical correlations to pile properties. Regarding numerical models, most data from Finite Element Method (FEM) can be found. They are not comprehensive, and most of the FEM results are sensitive to input parameters. The micro scale behaviour could change the mechanism of the soil-structure interaction. A DEM model was used in this paper to study the cyclic lateral loads behaviour. A non-dimensional framework is presented and applied to interpret the simulation results. The DEM data compares well with various set of published experimental centrifuge model test data in terms of lateral deflection. The accumulated permanent pile lateral displacements induced by the cyclic lateral loads were found to be dependent on the characteristics of the applied cyclic load, such as the extent of the loading magnitudes and directions.

***Keywords*—**Cyclic loading, DEM, numerical modelling, sands.

I. Introduction

THE offshore wind farm industry is experiencing rapid expansion in many countries. This situation is driven by the demand for renewable, sustainable and greener energy sources and strong public support. Increasing political and social pressures to reduce carbon dioxide emissions and society's dependence on fossil fuels have driven the demand for green sustainable energy sources [1]. Pile foundations are widely used to support various types of structures for situations when shallow foundations undergo excessive settlements or have insufficient bearing capacity. Monopile foundations are the main type used for wind turbines at present. They are always subjected to significant cyclic lateral loads due to wind and wave actions. Today the design of monopiles is carried out by modelling the pile as a beam and the soil as a system of uncoupled non-linear springs [2]. This method has successfully been used in pile design for offshore oil and gas platforms. The design methodology originates from tests on long slender piles with a small load eccentricity [3]. Even though this methodology was originally calibrated to slender piles, it is today used for design of large diameter stiff monopiles.

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The cyclic lateral loads mentioned above can influence aspects of the pile behaviour, including pile head displacements, pile secant stiffness, p-y curves, and so forth [4]. The characteristics of the cyclic lateral load include the cycle numbers, the cyclic load ratio (minimum load/maximum load in a cycle), and the maximum magnitude of load. Reese and Matlock [3] developed a method to consider the effect of cyclic loads. It is based upon a closed-form solution for a beam on an elastic foundation with a linearly increasing soil reaction modulus (LISM) that changes proportionally with depth. The LISM method provides a simple procedure for predicting the effect of cyclic lateral loads; however, it cannot explicitly account for effects of nonlinear soil response. According to field test results of instrumented piles subjected to cyclic loads, Reese, Cox [5] developed a semi-empirical, nonlinear p-y (soil resistance-pile deflection) approach, in which degradation factors obtained empirically are used to predict cyclic p-y relationships based upon degraded static p-y curves. Additionally, O'Neill and Murchison [6] suggested to generate cyclic p-y curves by reducing the static soil resistance for a given deflection. In both approaches mentioned above, the cyclic p-y curves are independent of the number of cycles. However, parameters required in this sophisticated approach are difficult to obtain from site characterization studies. Based on previous test data, Long and Vanneste [7] improved the p-y approach to consider the effect of the number of cycles. Nevertheless, only 50 or less cycles of lateral loads are executed in most of the tests considered. Moreover, the use of p-y curves often fails to account for the permanent deformation that accumulates with increasing cycles [8]. Therefore, additional cyclic load tests need to be conducted with many more cycles than previously to better understand the influence of cycle numbers.

In field tests, it is difficult to exert cyclic loading on monopiles with large diameters due to the limitations of test facilities and high costs. However, centrifuge modelling offers an effective way to understand the influence of cyclic loads on piled foundations. Compared with field tests, centrifuge tests are more convenient, efficient and cheaper. Centrifuge modelling provides an effective tool for researchers in geotechnical engineering as it allows the study of geometrically complex problems involving soil non-linearity. Centrifuge testing is, however, expensive and time consuming. Consequently, the number of tests performed in the study of a given problem is usually low. In addition, there are limitations on the amount of data that can be obtained during a centrifuge test. For these reasons, it is often beneficial to supplement a centrifuge study with numerical analyses. The numerical analyses can provide additional insights into the observed behaviour from the centrifuge experiments and allow investigation of certain experimental conditions.

The DEM is referred to, by Cundall and Strack [9], as the particular discrete element scheme that uses deformable (soft) contacts and an explicit time-domain solution of the original equations of motion. The Particle Flow Code in 2-Dimensions (PFC2D) is a programming code which is developed by Itasca. This software uses the DEM to simulate the movement and interaction of circular particles and observe their strain and fracturing behaviour, and all DEM programs allow finite displacements and rotations of discrete bodies, including complete detachment [10]. PFC2D can model either bonded (cemented) or unbounded (granular) group of particles [11], and also particles of any shape using the clump logic. Therefore, it is a powerful tool to simulate complex problems in solid mechanics, rock mechanics, and granular flow. At the same time, it allows for a detailed study of the micromechanics, such as the force networks formed by a granular media. Therefore, DEM is an attractive candidate for this task as it can replicate complex soil behaviour with the use of relatively simple inter-particle contact models.

In this research, a series of cyclic lateral load tests were conducted in the DEM-centrifuge model. The frequency of cyclic loading used in model was discussed. Also, the influence of cyclic lateral loads on the pile lateral displacement is investigated.

II. DEM Modeling of Centrifuge Model

A. Sample Characteristics and Model Setup

Table I shows the model parameters used in numerical model. According to the 2D PFC manual, the particle normal stiffness is twice its Young' modulus.

In the 2D PFC model, the boundary was first set in such a way that the size of the model was the same as that of Klinkvort [12]. The width of model is 0.6 m and depth is 0.55 m. Rigid walls were used to model the boundary. For the generation of particles. At the first stage, when the initial average porosity was nearly reached, the model was cycled to equilibrium. At the second stage, the special gravity (100 *g*) was added, and the PFC model was cycled to equilibrium again. This moment, the porosity was the final average porosity. At the third stage, before the pile was formed, the particles inside the same area were deleted. In this research, "clump" was used to model the rigid pile with a finite surface roughness. The system was then cycled to equilibrium again with the pile in place. The detailed sample preparation process was described as "GM" method.

All DEM analyses in this investigation were performed using the DEM-centrifuge program. Fig. 1 shows a sketch for analysis of pile-soil interaction and Fig. 2 gives the particles size distribution. l_L means the penetration depth, l_e is the load eccentricity. The PFC model of centrifuge test was simulated a solid steel pile with diameter d_{pile} = 45 mm and penetration depth 0.2m. The material modelled is composed of disks with a maximum diameter of 9.0 mm, a minimum diameter of 6.0 mm, an average grain diameter d_{50}=5.85 mm and uniformity coefficient $C_u = d_{60}/d_{10} = 1.26$.

TABLE I
INPUT PARAMETERS FOR DEM SIMULATION

Symbol	Parameters	Value
ρ	density of sand particles (kg/m^3)	2650
d	particle diameters	Fig. 2
d_{50}	sand grain size (mm)	5.85
μ	friction coefficient of the particles	0.5
E_p	sand young's modulus (Pa)	4e7
k_n	contact normal stiffness of particles (N/m)	8e7
k_s / k_n	particle stiffness ratio	0.25
k_n	contact normal stiffness of walls (N/m)	6e12
k_s / k_n	wall stiffness ratio	0.25
-	initial average porosity	0.25
-	final average porosity (after add gravity)	0.185
γ	Bulk unit weight (kN/m^3)	2115.3

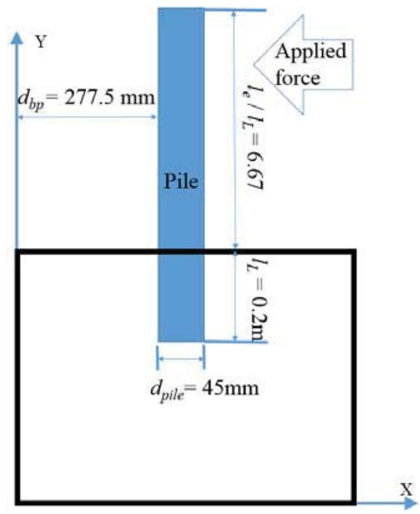


Fig. 1 Schematic view of the PFC model

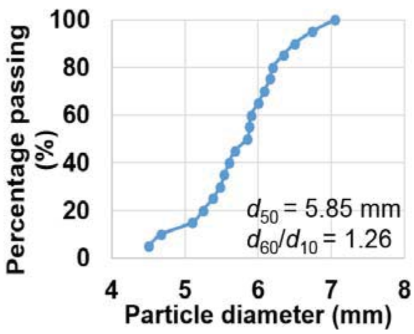


Fig. 2 Distribution of grain sizes in DEM analyses

Fig. 3 describes the comparison of average lateral and vertical stress distribution for different depths and shows *K*o is reasonable.

The pile was treated as a rigid material in view of high rigidity of a typical monopile, hence the consideration of bending moment was ignored. The vertical load and lateral load was applied to the ground surface on the top of pile.

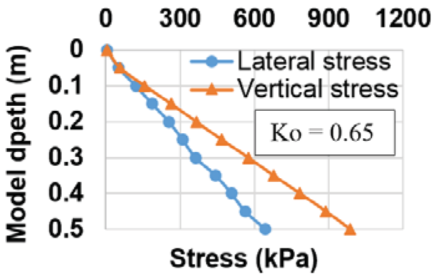


Fig. 3 Average lateral and vertical stress [13]

B. Centrifuge Laws and Dimensionless Analysis

In order to compare with a 1/100 scale centrifuge experiment on drained sand conducted at 100 g that modelled the behaviour of monopile foundations for offshore wind turbines, the particles gravity in DEM-centrifuge model is also modelled at 100 g. The response of the numerical centrifuge model will represent the behaviour of the prototype pile according to the scaling laws of centrifuge modeling given in Table II.

TABLE II
CENTRIFUGE SCALING LAWS [14]

Parameters	Model/Prototype
acceleration (m/s^2)	N
force (N)	$1/N^2$
stress (N/m^2)	1
strain	1
rotation	1
frequency	N
displacement (m)	$1/N$

The definition of dimensionless analysis is shown in Fig. 4. The gravity field was increased to obtain a scaling factor of approximately 100. This resulted in prototype piles with a diameter of 4.5 m and penetration length 20 m. The test program for the cyclic tests can be seen in Table III. $\hat{Y}$ was calculated by using (4). Y is the displacement of top pile under lateral loads. In the (1), d is diameter of pile, γ means the unite weight.

As shown in Fig. 3, the maximum displacement can therefore be determined. The maximum displacement is found as the displacement when the load is at the maximum of each cycle.

Normally dimensional analysis is used to transform results from model to prototype scale [15], however, this requires some knowledge of the relevant phenomena to be able to determine the governing parameters for lateral loading of piles, e.g. Randolph [16]. Quasi-static lateral loading of the monopile is assumed in this analysis, with no pore pressure build up during loading. The normalized force and deflection are defined as (1) and (4).

$$\widetilde{P} = P/(\gamma d^3) \quad (1)$$

$$\zeta_b = \frac{\widetilde{P}_{max}}{\widetilde{P}_R} \quad (2)$$

$$\zeta_c = \frac{\widetilde{P}_{min}}{\widetilde{P}_{max}} \quad (3)$$

$$\widetilde{Y} = Y/d \quad (4)$$

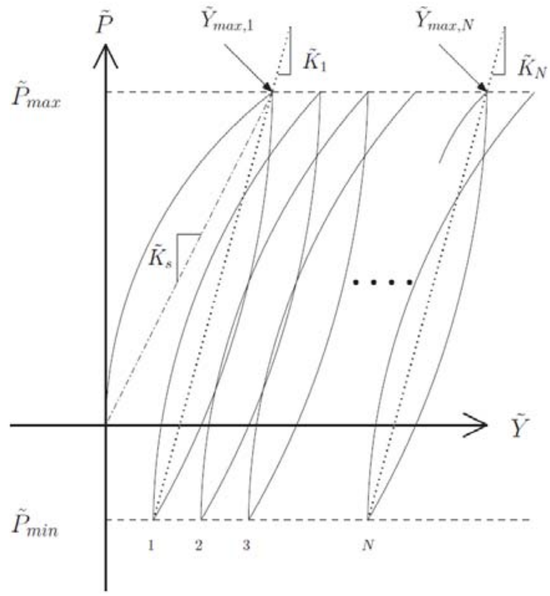


Fig. 4 Schematic drawing of determination of secant stiffness and maximum accumulation of displacement [12]

Here P_{max} and P_{min} are the maximum and minimum applied lateral force in the cyclic loading. P_R is the maximum bearing capacity found from the static test, which is, defined as the load correspond to a settlement equal to 10% of the pile diameter. A set of load characteristic constant are used to describe the cyclic loading. The load characteristics are denoted ζ_b and ζ_c. They are determined as shown in (2) and (3). ζ_b describes how close the cycles are carried out to the static bearing capacity. $\zeta_b = 1$ is therefore cycles carried out to the maximum bearing capacity. ζ_c describes the direction of the loading. For one-way loading $\zeta_c \geq 0$ and for two-way loading $\zeta_c < 0$. The value ζ_b is thus a measure of how close the cyclic loading is to the maximum load capacity, and ζ_c is defining the characteristic of the cyclic loading. From these non-dimensional parameters, a test program can be designed. The maximum capacity is found from the monotonic test. The cyclic loading is carried out using force control. Due to the PFC force control system it is always that the pile response is exactly as wanted. So this means the accuracy of numerical model is better than experiment.

C. Frequency

In Table III, there were summarised a series of numerical tests. The validity of the numerical model was verified by checking the pile load test data against a comprehensive published case. The centrifuge experiment tests performed by Klinkvort [12] were a single pile under lateral cyclic loads applied to the pile head at the top of pile.

Long-term cyclic loading of the wind turbine foundations may change the soil stiffness, and hence the resonant frequencies, which can lead to the accumulation of irreversible deformations. Site-specific spectral densities for wind and waves can be derived from available measured data, met-ocean databases or numerical models. The excitation ranges, 1Ω and 3Ω, and the realistic normalized power spectra representing aerodynamic and hydrodynamic excitation are illustrated in Fig. 5. So far, offshore wind turbines are designed with the 1st natural frequency, f_1, in the range between 1Ω and 3Ω; in the wind industry sector this is referred to as a "soft-stiff" structure. However, it is possible to design a "soft-soft" structure with the 1st natural frequency below 1Ω, or a "stiff-stiff" structure with the 1st natural frequency above 3Ω. The choice of frequency range for f_1 sets criteria for the stiffness of the foundation; in general, less steel is required for a soft structure.

TABLE III
SUMMARY DEM-CENTRIFUGE TEST PARAMETERS

T[1]	ζ_b	ζ_c	Diameter of pile (mm)	E[2]	ζ_b	ζ_c	Diameter of pile (mm)
T1-2	0.18	-0.5	45	E1-2	0.18	-0.46~ -0.32	28
T1-3	0.36	-0.37	45	E1-3	0.36	-0.46~ -0.32	28
T1-4	0.08	-0.5	45	E1-4	0.08	-0.46~ -0.32	28
T2-3	0.36	0.5	45	E2-3	0.25~ 0.29	0.36	28
T3-1	0.36	-0.5	45	E3-1	0.33 ~ 0.34	-0.5	40
T4-3	0.36	0	45	E4-3	0.15 ~ 0.36	0.05	40

In this table, the order of experiment is not continuous, because only parts of model tests were picked up for analysis. This sequence will be same as the future full detailed journey paper. [1]T means DEM modelling, [2]E means experiments.

As mentioned before in introduction, the frequency is very important for the cyclic loading test. Fig. 4 shows the typical excitation ranges of a modern offshore wind turbine. The frequency of waves and wind are the main reason of cyclic loading which applied on the pile of wind turbine.

Fig. 5 shows the main frequency of cyclic loading is about 0.1 Hz, this value has been widely used in the 1g experiment tests. In centrifuge test (100 g level), the value of frequency should be 10 Hz (see Table II). However, Table IV shows that the centrifuge test used lower frequency, and most centrifuge tests did not discuss the frequency a lot.

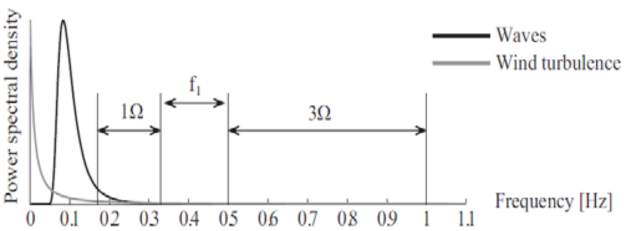
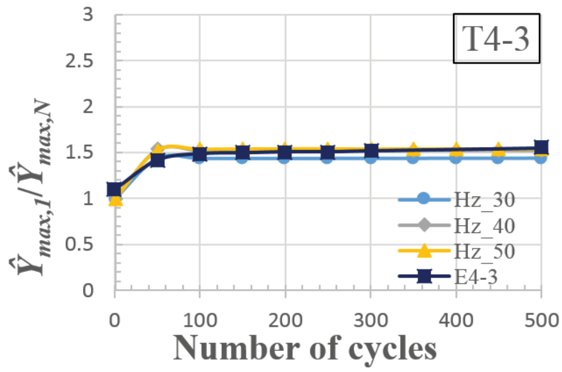


Fig. 5 Typical excitation ranges of a modern offshore wind turbine [17]

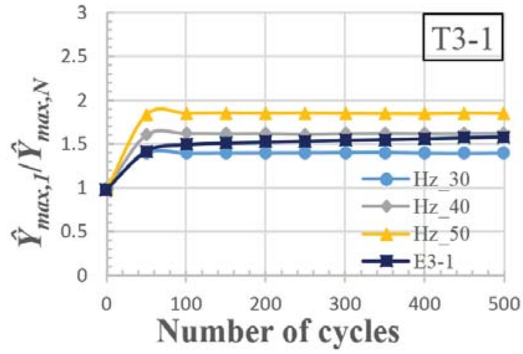
From Fig. 6, the results show the good match are at 40 Hz, therefore, in DEM-centrifuge modelling, the frequency was chosen 40 Hz. In DEM modelling tests, T4-3, T3-1, and T2-3 adopt the same ζ_b, this is slight different with experiment. The according tests in experiment used the range of ζ_b, so the values of DEM modelling take the maximum values of the range in experiment. For the ζ_c, the values are also nearly same as the experiment. As the good match, frequency 40 Hz was chosen in the following numerical model tests.

TABLE IV
SUMMARY FREQUENCY USED IN EXPERIMENT TESTS

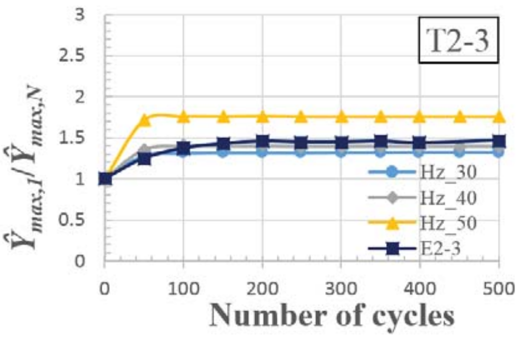
Number and author	Frequency (Hz)	g (N/m^2)
1, Leblanc, Houlsby [18]	0.106	1
2, Roesen, Ibsen [19]	0.1	1
3, Li, Haigh [20]	0.02-0.7	100



(a)



(b)



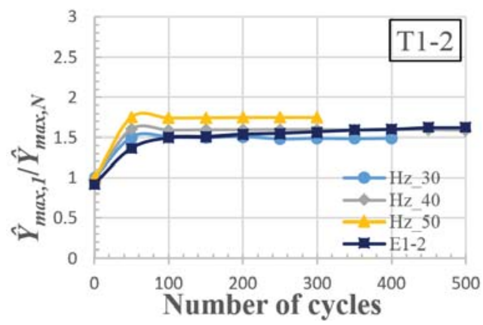
(c)

Fig. 6 Comparison of model and experiment results [12] at different frequency

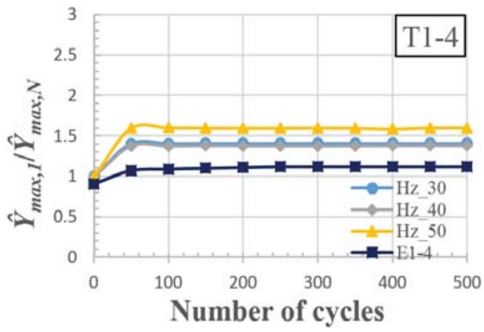
III. Results

From the Fig. 7, the results show that T1-2 is good compare. However, there is a little deviation in T1-4. This two tests used the same ζ_c and different ζ_b. The absolute value of ζ_c in DEM model are little bigger than experiment, but the comparison is good at T1-2. The reason is the ζ_b in T1-2 is bigger than T1-4 which means the results is sensitive during the lower values of ζ_b. When the values of ζ_b is increasing, ζ_c will not affect too much the accuracy between model and experiment.

Fig. 7 (c) shows the magnitude of displacement will increase when ζ_b grows as well.



(a)



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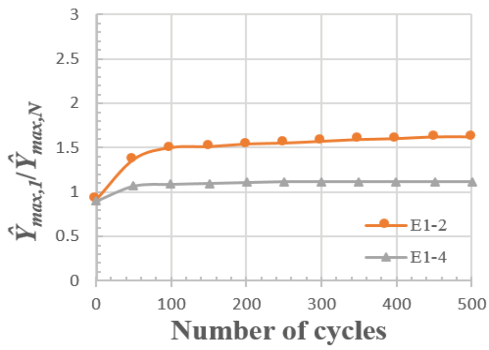
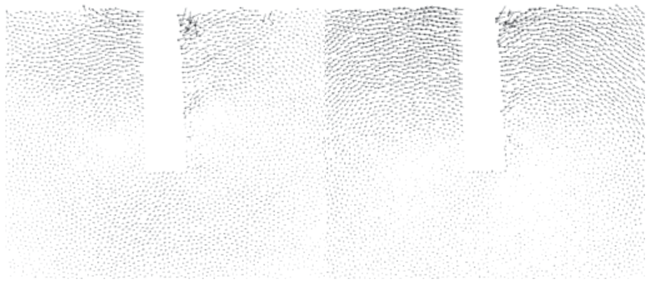


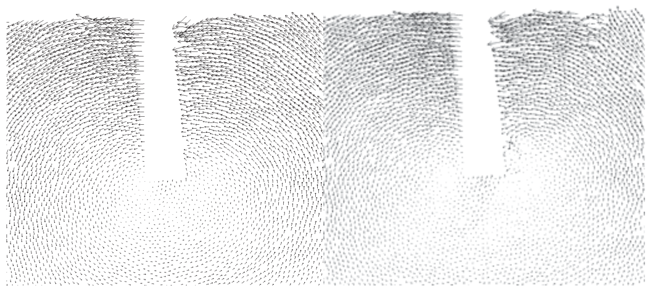
(c)

Fig. 7 Comparison of modelling and experiment data [12]

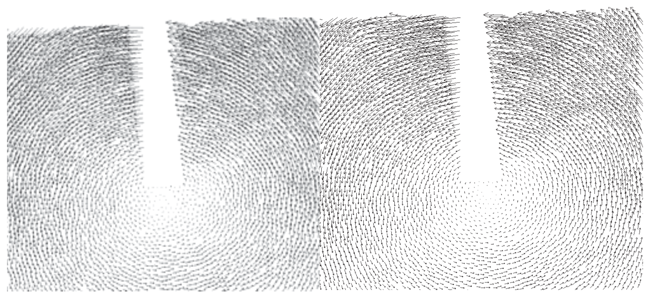
Fig. 8 indicates that the location of pile changes with the increasing cycle's number. And the magnitude of particles' velocity increase with the cycle number as well. Compare T1-4 and T1-2, for the same number of cycles, the ζ_b is bigger, the velocity is larger too. At the beginning of cycle, there are two whirlpools of particles velocity located at two sides of pile tip. With the increasing cycle number, there become only one velocity circle round under the pile tip.



(a) (b)



(c) (d)



(e) (f)

Fig. 8 Particles' velocities distribution comparison of T1-4 and T1-2: (a)(c)(e) are shown at 1, 10, 500 cycles (T1-4), (b)(d)(f) are shown at 1, 10, 500 cycles (T1-2)

IV. Discussion

In this paper, different examples of cyclic lateral load test have been described. All tests have been modelled by DEM-centrifuge model. One common factor for all the presented tests is that they have been modelled in dry sand. The sand located offshore where monopiles are installed, is dense sand but it is not dry. This means the condition for a real monopole could be drained, partial drained and maybe undrained even for sand. It is important to understand that the tests presented here only represent the fully drained case.

The next step in the research is to add the micromechanics to the soil sample. This enables the possibility of understanding the mechanisms surrounding soil and accumulated displacement, corresponding to offshore conditions.

The number of cycles is another issue which has to be taken into account. The cyclic tests presented here have a total number of cycles 500. This is much more than the number of cycles from the previously tests but the number still has to be increased.

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