A Novel Small-Scale Model Testing Device for Laterally Loaded Piles

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ABSTRACT: In 2014, NGI and BP America Inc. developed and built a novel model testing device for measuring the response of cyclic lateral loaded piles. Objective of this device is to assess site-specific cyclic p-y backbone curves on intact soil specimens under in-situ stress and density conditions. Primary application of these curves is in structural fatigue analysis. For that purpose, the model pile is subjected to sequences with symmetric cyclic displacement amplitudes, where the load level is well below the pile capacity limit. The performance of the p-y apparatus, as the device is called, has been demonstrated by means of an extensive testing program on different soil types. The results were compared with centrifuge test data. It was found that the measurements made in the p-y apparatus agreed very well with both the centrifuge test results and the numerical framework, which was proposed some years prior to the development of the device. Despite the simplicity of the cyclic load history used in these tests, the actuation system is capable to apply more complex cyclic load histories allowing both asymmetric loading, force-controlled testing, and even random load histories. This enables to study the pile response under general monotonic and cyclic loading. An important design aspect, in particular for renewable offshore energy structures, is the Serviceability Limit State (SLS). The general suitability of the p-y apparatus for that application case was investigated recently and the plausibility of the measurement was checked. This article introduces this novel model testing device, shows the performance for its original purpose, and presents preliminary results of the recently conducted more complex cyclic load histories.

Keywords: 1G pile model testing; cyclic p-y curves; fatigue; serviceability.

1 INTRODUCTION

Soil structure interaction has become in the recent years increasingly important in offshore geotechnical engineering, particularly with the rise of offshore wind energy turbines. But also, the development of very deep and remote oil and gas reservoirs demands more advanced design approaches to reduce the risk of failures.

Foundation capacity requires information of only the soil strength, while strains are only relevant for compatibility reasons at failure of the soil body. However, soil-structure interaction design requires information of the complete stress-strain response of the soil. Even more complicated is the description of the soil response under cyclic loading, as it depends on the load amplitude and mean value, load frequency, duration and drainage conditions.

In order to cope with this complexity in the design, dedicated engineering models are required. One such model has been developed by BP for the structural well conductor fatigue design (Zakeri et al., 2019). The model proposes a framework for cyclic p-y backbone curves. The basic assumption is the existence of a cyclic attractor of the secant stiffness for a given symmetric and constant displacement amplitude. A pile segment subjected to a constant cyclic displacement amplitude Δy will respond with a cyclic resistance amplitude Δp, which gradually decreases with number of applied load cycles N. The existence of the cyclic attractor postulates that Δp will approach a constant value; denoted in the BP design framework *steady-state*. At steady state can be calculated a secant stiffness viz.

$$K_{Sec.,SS} = \frac{\Delta p}{\Delta \mathrm{y}} \tag{1}$$

A cyclic p-y backbone curve can be constructed from the secant stiffness values for different displacement amplitudes.

This framework has been developed based on a series of centrifuge tests. The results of these tests were normalized with the respective static shear strength of the intact specimen. This allows to apply the framework to all type of soils, given that the static shear strength is known. However, since only a limited number of soil types have been tested so far, an application in real projects requires laboratory testing to increase confidence in the framework. For that purpose, NGI developed the so-called p-y apparatus shown in Figure 1 (Zakeri et al., 2017).

2 THE P-Y APPARATUS AND TYPICAL TEST RESULTS

The underlying idea of this apparatus is to assess the steady state secant stiffness on intact specimens taken with standard piston samplers. That means that the soil specimen has an outside diameter of 68mm and a length of 100mm or 200mm, respectively. The specimen is fully confined by means of a rigid cylinder and two special designed endcaps. Through these endcaps is installed a model pile with D=10mm in diameter, which goes through the whole specimen.

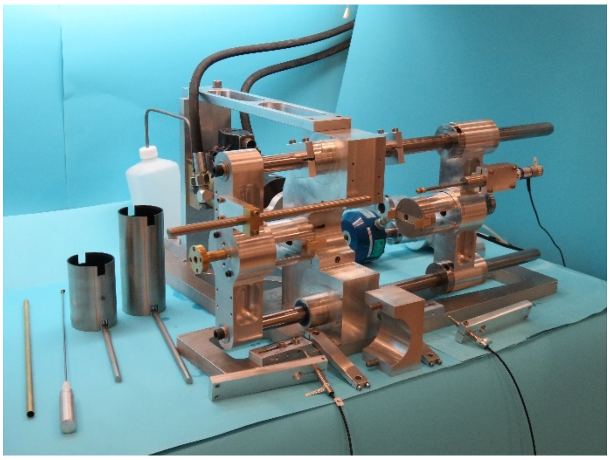

Figure 1. p-y apparatus including 2 different sized specimen cylinders and model piles.

After installation of the model pile, the specimen is consolidated to in-situ stress level. At end of the consolidation, the model pile will be attached to a loading frame and a hydraulic actuator applies packages with constant cyclic displacement amplitudes. The number of cycles per package depends on the soil type and behaviour, but typically ranges between 500 and 2500. The cyclic displacement amplitude y/D varies between 0.125% and 8%, where the amplitude is doubled from package to package. Typical loading frequencies are between 0.1Hz and 1Hz.

Although only the response in the last cycle is required in the BP design framework, the complete development of the secant stiffness with number of cycles is reported. In addition, the corresponding hysteretic damping is evaluated and reported, which is of importance for structural fatigue damage analysis. Example results of the normalized steady-state secant stiffness and corresponding damping ratio are presented on Figure 2 and Figure 3.

Figure 2 shows in addition two trend lines based on the BP design framework, which was established based on best fit of centrifuge data.

The measured secant stiffness values agree well with the trend line, but seem to underestimate the stiffness for low displacement amplitudes. However, a closer inspection of the trend lines in this area reveal an unrealistic shape of the p-y curve where the pressure does not start from zero at zero displacement, but rather approaches a constant value. The measurements, however, predict a consistent and realistic p-y curve.

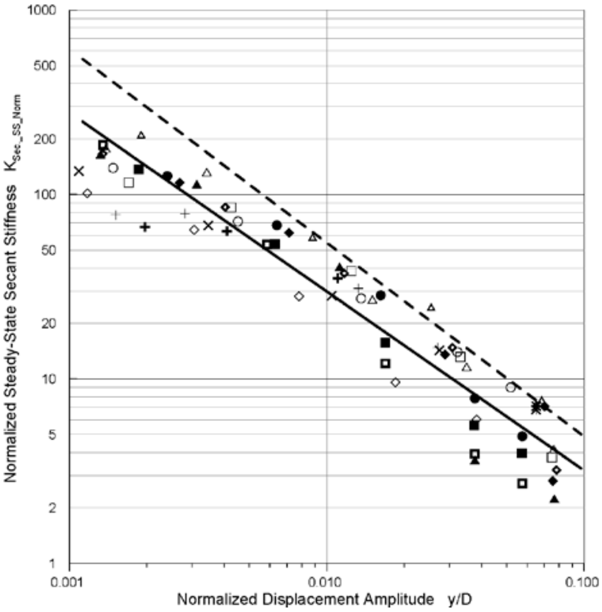

Figure 2. Normalized secant stiffness and trendlines developed based on a comprehensive series of centrifuge tests (caption shown in Figure 3)

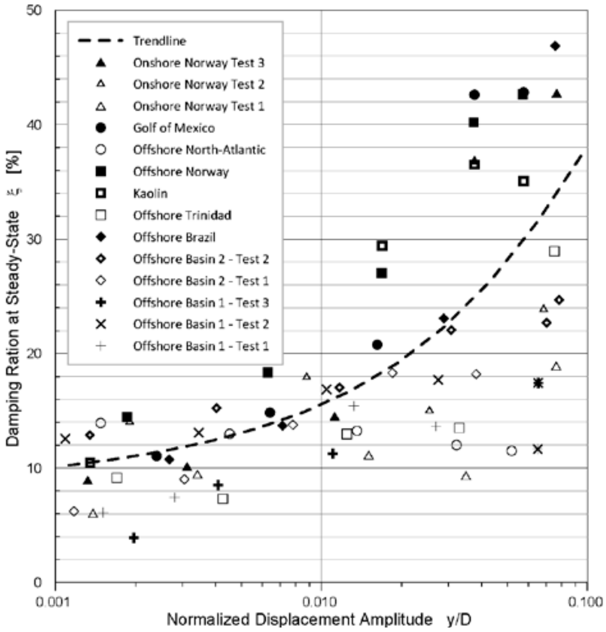

Figure 3. Equivalent damping ratio at steady state and trendline based on the shown data points

The damping values show a plausible trend, but with a large scatter. The dashed line in Figure 3 represents a best fit with a large standard deviation for increasing cyclic displacement amplitudes.

3 SERVICEABILITY TESTING

The p-y apparatus uses an MTS hydraulic actuation system for applying monotonic and cyclic loading. This opens the possibility to test the pile response to generalized cyclic loading. Of particular interest for designers is the foundation serviceability, that means the accumulated displacement due to repeated cyclic loading.

Table 1. Index properties of Kaolin

Parameter	Unit		Value
Specific density	ρ_s	[g/cm^3]	2.59
Clay content		[%]	55.7
Grain size	D_{60}	[mm]	0.003
Plastic limit	w_P	[%]	28
Liquid limit	w_L	[%]	56.1
Plasticity index	I_P	[%]	28.1

In 2018/19, a series of tests has been conducted to study the general suitability of the p-y apparatus for the application to serviceability problems. For that purpose, the first-time load-controlled tests were performed. To ensure repeatability and consistency of the tests, two bins with re-constituted Kaolin clay were prepared. The properties are summarized in Table 1. After consolidation to 80kPa, the blocks of Kaolin were divided into 9 square samples (see Figure 4). Only one specimen can be obtained from each sample.

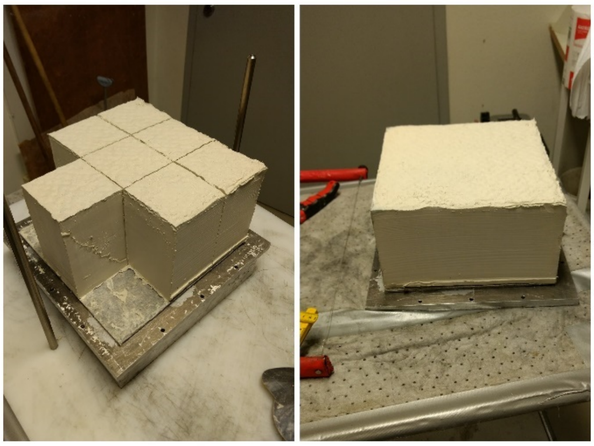

Figure 4. Reconstituted blocks of Kaolin for p-y testing

The sample was than trimmed to fit into the specimen cylinder and built in into the p-y apparatus. After installation of the model pile, the specimen was consolidated in three steps to a final consolidation pressure of 120kPa. The DSS shear strength of this material is approximately 25.5kPa.

The series comprises tests with different cyclic load histories, all performed at the same material with the same initial stress and density state. The tests were conduced such that the specimen height was kept constant during cyclic loading. Due to constructional reasons, the specimen is not water tight and could drain through the endcaps. A back pressure cannot be applied.

4. TEST RESULTS

Figure 5 shows a test with a constant average load of 40kPa and 5 packages with cyclic load amplitudes of 40kPa, 60kPa, 80kPa, 60kPa and 40kPa. 500 cycles per package were applied except for the largest amplitude where 1000 cycles were applied. The loading frequency was 0.25Hz.

It can be seen, that the accumulated average displacement increases continuously, and the accumulation rate becomes larger for larger load amplitudes. When decreasing the load amplitude again, the accumulation rate also decreases and is eventually smaller than in the corresponding package with same load amplitude applied prior to the peak phase.

The cyclic displacement amplitude is small(er) and almost constant for the two first load packages but increases continuously in the third package with the 80kPa load cycles. The specimen shows a softening behaviour. When decreasing the load amplitude again, the corresponding displacement amplitude becomes continuously smaller. The specimen shows a hardening or setup behaviour and seems to regain resistance. But the cyclic amplitude remains larger than measured in the corresponding package prior to the peak phase.

A second test is shown on Figure 6 where a constant cyclic amplitude of 40kPa is applied but the average load is varied in 8 packages from 40kPa, 80kPa, 40kPa, 0kPa, -40kPa, -80kPa, -40kPa and 0kPa. Again, 500 cycles per package with a frequency of 0.25Hz was applied.

It can be seen, that the accumulated average displacement follows the average load and seems to be completely reversable when changing the loading direction. As for Test 4, shown on Figure 5, the accumulation rate is a function of the load intensity.

The cyclic displacement amplitude, however, seems to be almost constant and independent on the average load. An exception are the packages without an average load (i.e. p_{av}=0kPa), where significant larger displacement amplitudes are observed.

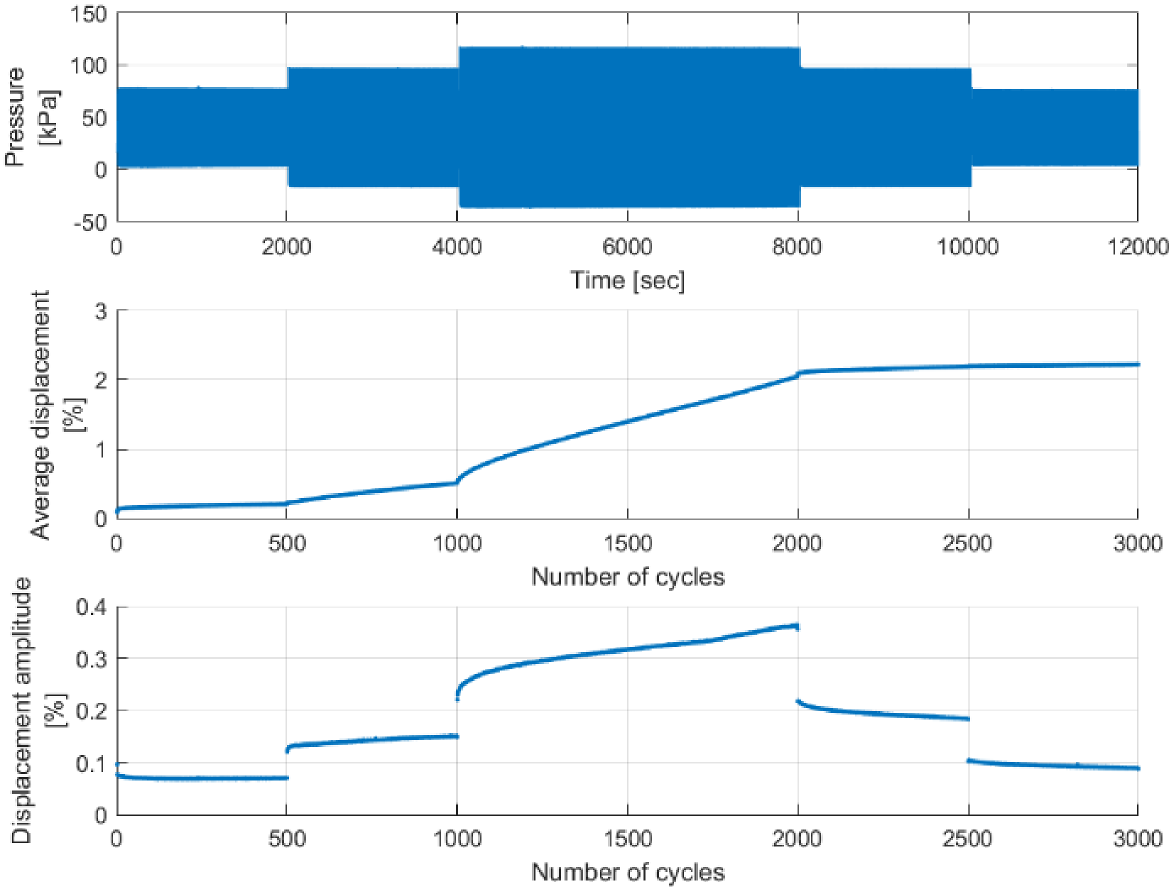

Figure 5. Test 4 with constant average and variable cyclic loading

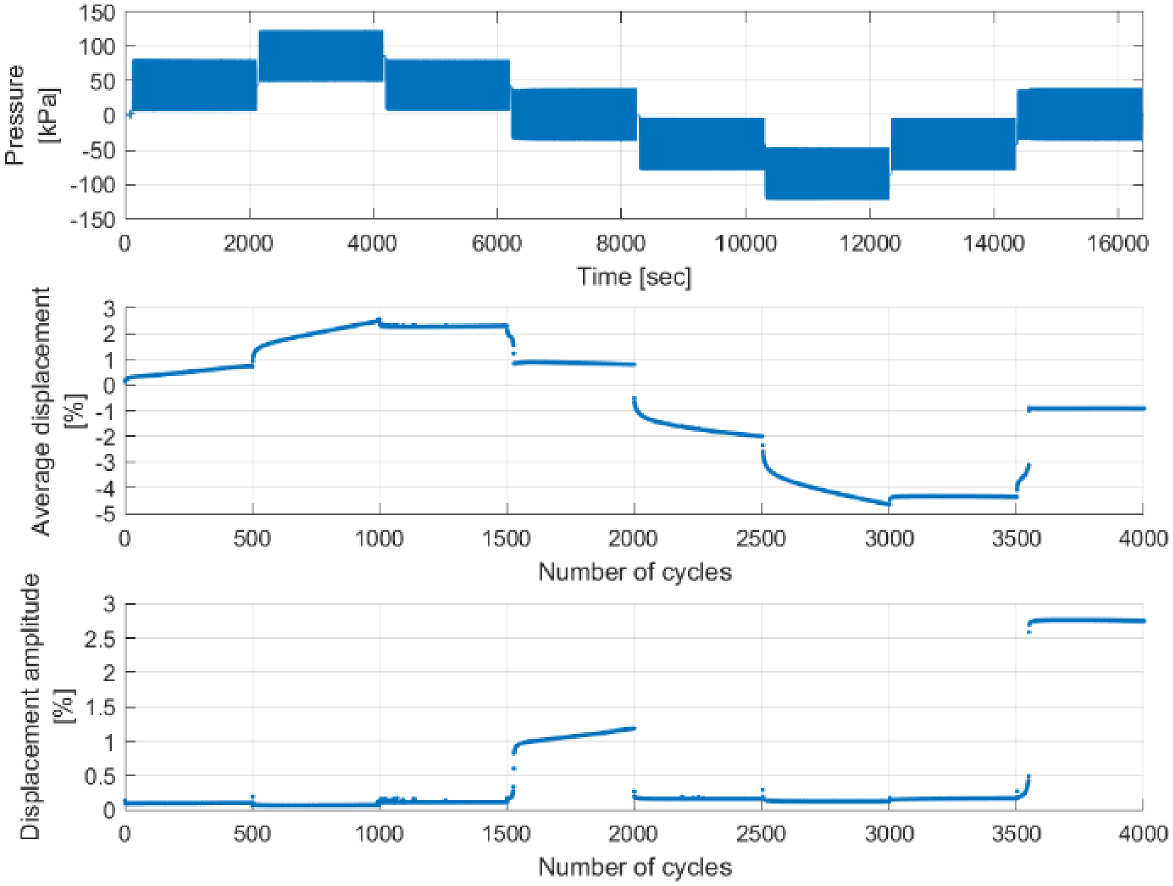

Figure 6. Test 5 with variable average and constant cyclic loading

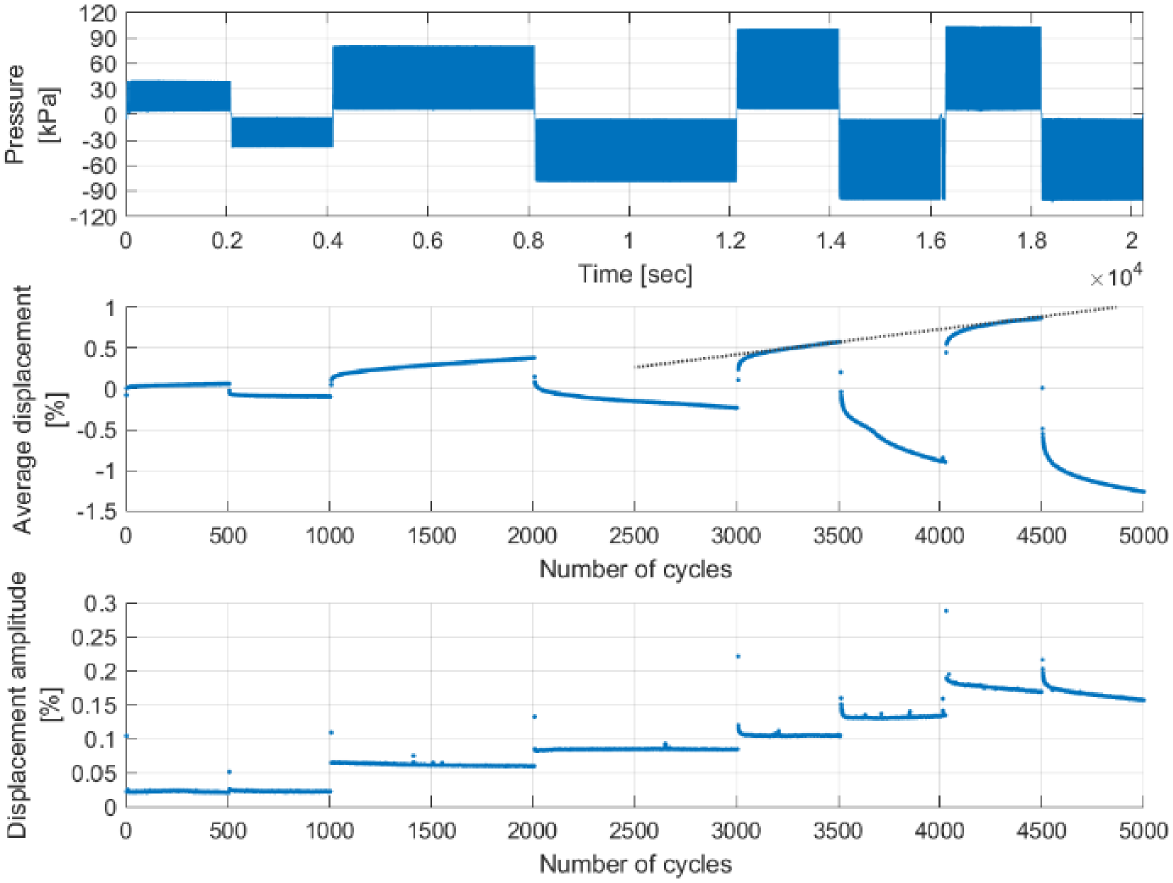

Figure 7. Test 2 with constant cyclic to average load ratio but alternating direction of average load and increasing cyclic loading

The last test presented is Test 2 shown on Figure 7. Like test 5 shown on Figure 6, the direction of the average load was changed. In addition, though, also the value of both the average and the cyclic amplitude changed such that the ratio between cyclic and average load was equal 1 or -1, respectively. The number of load cycles varied between 500 and 1000, all at a frequency of 0.25Hz.

Like for the other two examples, an increase of the average accumulated displacement can be seen for increasing load intensity. Furthermore, the average displacement seems to follow the average load level and even changes the direction accordingly. However, after each reversal, the specimen seems to be "softer", following the previous tendencies independent of the reversal. On Figure 7 is shown a trend line over the fourth and second last package. The reversal in the third last package seems to not affect the accumulation rate nor the absolute value. In fact, it seems that the direction did not matter, and it may be expected that the accumulation rate and absolute value of the average displacement would be the same in the second last package if no load reversal would have been made in the third last package.

Also, the cyclic displacement amplitude gets larger for increasing load amplitude. However, there seems to be a tendency for an increased cyclic resistance, since the amplitude slightly decreases within each package at constant cyclic load amplitudes.

5. DISCUSSION

The three examples presented in the previous section show, that plausible test results can be obtained using the p-y apparatus. Comparing the results qualitatively with laboratory tests (Wichtmann, 2016) and numerical models (Niemunis et al., 2005), reveal a quite consistent behaviour. The cyclic flow rule proposed by Niemunis et al. (2005), postulates an increased accumulation rate (i.e. the average strain per load cycle) depending on the cyclic amplitude and the ratio of cyclic to average load. This agrees with the observations in Test 4 and test 5 shown on Figure 5 or Figure 6, respectively.

Very limited literature is found on laboratory or model tests with reversals, which could explain the decrease in accumulated displacements as seen in Test 5 (Figure 6). Also, the setup effects, that means the increase in cyclic resistance during loading, as observed in Test 2 (Figure 7), has not been explicitly reported in the literature. However, setup effects in laboratory tests are known and have been reported by Andersen (1988) at the example of undrained cyclic DSS tests with consolidation periods between the cyclic load packages. The cyclic resistance increased in each package due to re-consolidation and compaction in the resting periods. Although, the specimen height was kept constant in the p-y apparatus, local consolidation effects are still plausible to happen; the largest pore pressure will be generated around the pile, but due to the high consolidation coefficient of Kaolin clay, it is likely that the pore pressure dissipated radially (and axially through the endplates). Specimens of natural clay teasted in the p-y apparatus showed after dismounting a zone around the pile which seemed to have a different water content than the rest of the specimen (Zakeri et al., 2017). Kaolin clay, however, is white and such a zone can hardly be identified.

The soft response in Test 5 at zero average load may indicate a gap around the pile. However, since the displacement amplitude was very small, the observation may be also caused by a highly disturbed zone in the vicinity of the pile. The fact that the amplitude in the last package is almost twice the amplitude of that in the fourth package supports this assumption. Only the soil at the side of the pile to which an average load was applied in the previous packages is softer, whereas the soil at the other side is not significantly affected. When applying an average load also in the opposite direction, the soil at both sides become equally soft, hence the cyclic amplitude in the 8th and last package is almost twice as large.

6. CONCLUSION

The results show the general suitability of the p-y apparatus for serviceability testing. Using reconstituted Kaolin allowed to compare the results. But the drainage coefficient of Kaolin is high, and it is believed that water drained out through the endcaps.

It is planned to perform further tests varying more systematically the cyclic load histories. Furthermore, it is considered to perform the tests under constant axial loading allowing the soil specimen to consolidate continuously. Such tests are currently conducted, but with focus on the secant stiffness. For that purpose, symmetric cyclic load amplitudes are applied. The first tests showed promising results and agreed qualitatively well with numerical predictions. It is thus expected, that the same configuration can be used for serviceability testing as well.

7 ACKNOWLEDGEMENTS

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