Test on Cyclic Lateral Loaded Piles in Sand

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Abstract

The following paper deals with experiment on a lateral cyclic loaded pile in sand. Piles exposed for lateral cyclic load are often used in off shore foundation and bridges. The experiments are conducted at Griffith University at Gold Coast Campus. The experiment setup is recently developed and can be used for several other experiments such as horizontal soil movement and also other cyclic loading.

In this paper, four experiments are conducted. The aim is to investigate the effect of cyclic loading in the form of soil response and the distribution of bending moments in the pile. Furthermore, the pile deflection and rotation is also measure. The results are compared in different diagrams in order to visualize the difference. The parameter that is change in the four experiments is the cyclic program, the magnitude of the load and the length of the pile.

Finally, the results are compared and discussed in order to make a conclusion on the results.

1. Introduction

All piles supporting offshore construction are subject to cyclic loading because of waves, tide and wind. This can be lateral cyclic loading with different force and period. Due to the nature of these loads, the loads can be one way or both ways. In design of offshore constructions, it is therefore important to be able to predict the response of the soil subject to lateral cyclic loading.

At Griffith University, an apparatus to investigate lateral soil movement, one way lateral pile loading and vertical pile loading is developed with support from the Australian Research Council. The apparatus consists of a box where the upper part can move lateral. The results are measured with strain gages and LVDTs. The data is collected on a computer and manually.

In the present paper, the statically P-y curve is determined. Using the P-y curve, 3 one way cyclic loading tests are conducted on the pile with different loading programs. The effect of loading program is investigated. The results are presented and analyzed in this paper.

2. Apparatus and Test Procedures

The apparatus and the setup are described by Guo and Ghee (2004) and are only briefly described in the following section.

2.1. The Box and the Sand

The box is 1 by 1m and 0.8m tall. It consists of a bottom box which is fixed. This is 0.4m tall. The upper part consists of a number of frames which can be exposed for lateral movement. However, in this experiment the upper part is also fixed. The sand is dense oven dried medium grained quartz, Queensland sand. The unit weight is 16.27kN/m^3 and the angle of friction is 35.5^o. The grain size for 50% is D_{50} equal to 0.32mm, cf. Figure 2-1.

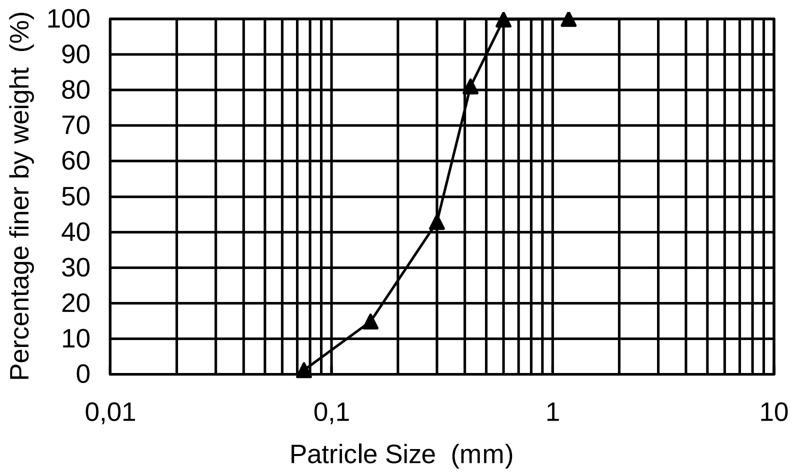

Figure 2-1: *Distribution of particle size.*

The soil displacement around a lateral loaded pile is less than 5% in a distance of 5D from the pile where D is the pile diameter (Tominaga et al., 1983). This means that the shear box is large enough to be used for the experiment.

2.2. The Pile

The pile is made of aluminum and is 1200mm long, have an outer diameter of 32mm and a wall thickness of 1.5mm. In order to obtain results for the experiment, there are attached several pairs of strain gages on the pile according to Figure 2-2. To support the strain gages, tape is used. This makes the pile thicker but since it is tape the difference is neglected.

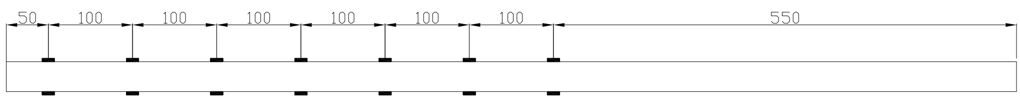

Figure 2-2: *Placement of strain gages on pile.*

Furthermore, a hook is placed on the pile in the length e above the ground level. The pile is driven into the sand using a piston to a depth L_e. A illustration of the test setup is given in Figure 2-3.

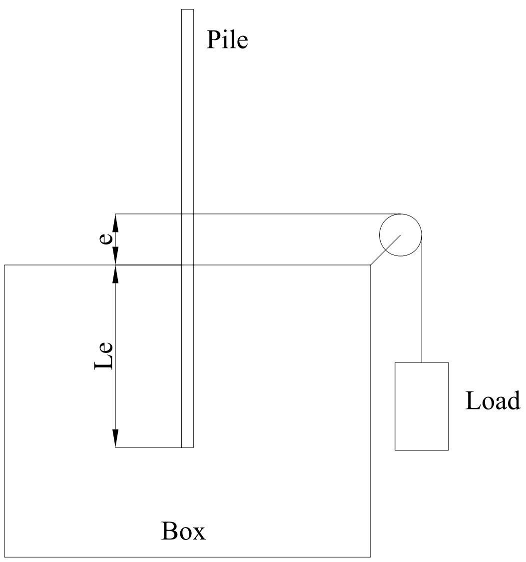

Figure 2-3: *Test setup.*

The strain gages are connected to a computer through an adaptor. Since the strain gages are exposed for electricity they are slowly warming up. In order to measure this effect, a dummy strain gage is used. In Figure 2-4, both adaptors and the dummy strain gage are shown.

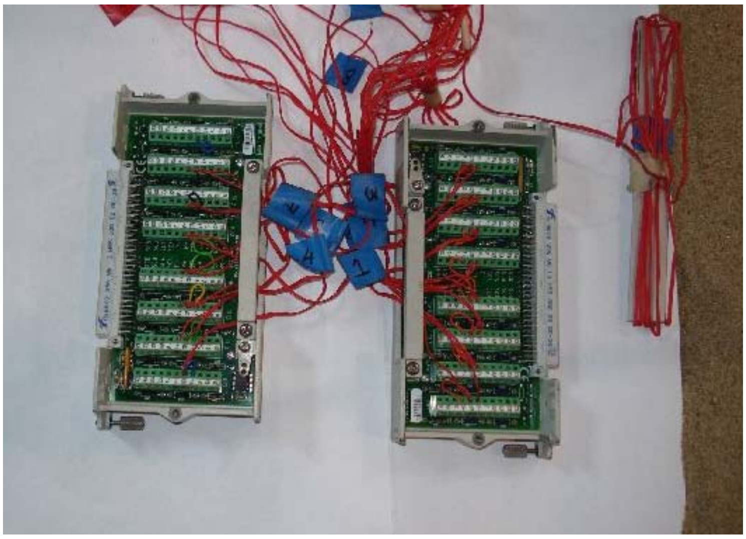

Figure 2-4: *Adaptor and dummy strain gage.*

The computer collects the data from the strain gage and the data are also collected manually.

The rotation of the pile is measured with 2 LVDTs (linear variable difference transducer). They are placed with a certain distance and by comparing the movements; it is possible to calculate the rotation.

According to Verdure et al., (2003) there will be scale effect between the grain and the pile diameter if the following equation is not fulfilled, where B is the pile diameter

$$\frac{B}{D_{50}} < 100 \qquad (.1)$$

It is noted that the result is 100 which means that there might be scale effects. Furthermore, it is noted that the sand around the pile have been subject to compression during the driving, since it is observed that there is a two centimeter hole around the pile. This hole was covered before the test was started.

2.3. Test Procedure

The pile is in all tests installed with a hydraulic pump and the pile resistance is measured. Afterward, the strain gages are connected to a computer which collects the data. The LVDTs are also installed. Common to all tests are that there are no vertical loading during the test. The pile is the applied the lateral loading program and after the loading program, the yielding capacity is found for each test. The test setup is shown in Figure 2-5.

Figure 2-5: *Test setup with lateral load applied.*

3. Test Results

The test results are given in the following. The results are obtained from the strain gages, the LVDT's and the load on the pile. These results are treated in an Excel VBA spreadsheet. The equations that are used to get the rotation, moment, shear force and soil reaction are the Bernoulli Euler beam equations. The equation assumes small movements and is only valid for long thin beams. This means that the deflection of the pile it self must be small and the effective length should be longer than 10 times the diameter. The pile is long and thin enough and the deflection of the pile is checked for each test. When the moment of inertia and Young's modulus does not vary over the length the equation is given by

$$p = EI\frac{d^4 w}{dx^4} \tag{.2}$$

Where the 2 following equations can be found with equilibrium

$$V = \frac{dM}{dx} \tag{.3}$$

$$p = \frac{dV}{dx} \tag{.4}$$

How these equations are solved numerical is not described further in this paper.

In the following, the P-y curves, bending moment, shear force, soil reaction, rotation and deflection are analyzed for the 4 test.

3.1. Static Loading (L=1200mm, L_e=500, e=115mm)

The static loading test was conducted to determine the P-y curve and failure force for the pile. Furthermore, 6 unloading reloading cycles were conducted. These cycles proves that the sand is able to harden and also that the reloading curve response elastic to the applied reloading force. The P-y curve is shown in Figure 3-1, where each square indicates a test result.

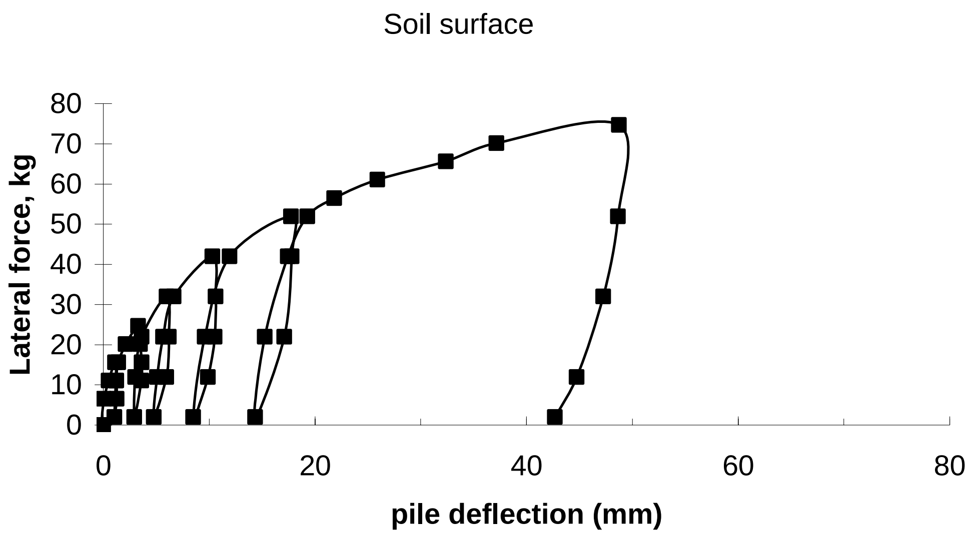

Figure 3-1: *P-y curve for the pile.*

As the figure shows, there is no simple yielding point. Therefore other references must be used to determine the yield load.

By assuming Gibson soil it is possible to derive a failure load of [Broms, 1964]

$$P_u = \frac{0.5BL^3K_p\gamma}{e+L} \tag{.5}$$

where

P_u	is the failure load
B	is the pile diameter
L	is the embedded pile length
K_p	is the passive soil pressure given by $tan^2\left(45+\frac{\varphi}{2}\right)$
e	is the load eccentricity

The result from (.5) yield a failure load of 864N which is equal to 88kg. By comparing this result to Figure 3-1 it shows that (.5) yields a too high failure load and it is therefore unsafe. However, the result is not far from the failure load of the tested pile.

A closed form solution which takes the non linear response of the soil into account is used. The method is developed by Guo, (20??) and gives the P-y curve for the soil when the soil response as Gibson soil. The input parameters are given in Table 3.1. The method is not described further in this paper.

Ko	50,000 [kN/m^4]
L	0.500 [m]

E	0.115[m]
r0	0.016[m]
γ	16.27[kN/m^3]
Kp	tan^2(45 + φ /2)
Ar	1.3 γ Kp^2
Φ	35.5^o

Table 3.1: *Parameters for the closed form solution.*

The result is plotted on top of the test results, cf. Figure 3-2. Note that the closed form solution under predicts the P-y curve. However, the shape of the two curves is alike since the both goes from elastic behavior at about 10mm deflection.

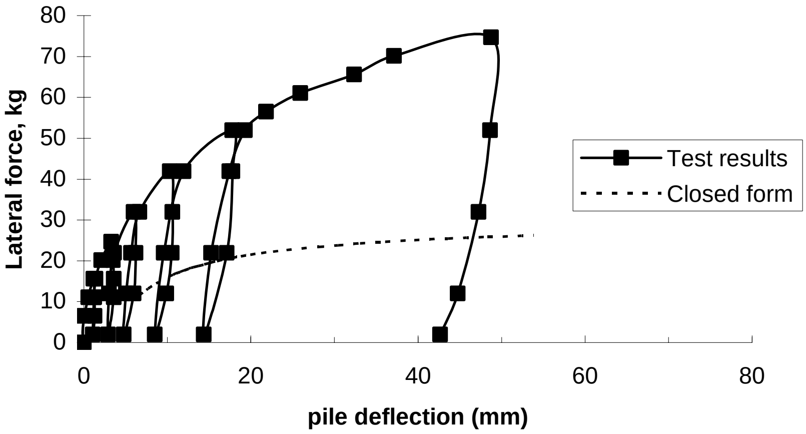

Figure 3-2: *Comparison between test results and closed form solution.*

In order to make a better fit, some of the parameters are changed. Furthermore, the effect of dilation is taking into account by redefining A_r and the fittet parameters and the new definition of A_r is given in Table 3.2.

	Low	High
Ko	200,000 [kN/m^4]	200,000 [kN/m^4]
L	0.500 [m]	0.500 [m]
e	0.115[m]	0.115[m]
r0	0.016[m]	0.016[m]
γ	16.27[kN/m^3]	16.27[kN/m^3]
Kp	tan^2(45 + φ /2)	tan^2(45 + φ /2)
Ar	tan^2(45 + ψ/2)γ Kp^2	tan^2(45 + ψ/2)γ Kp^2
φ	35.5^o	35.5^o
ψ	10^o	20^o

Table 3.2: *Fitted parameters.*

The changed values are K_0 φ and A_r. The new results for the improved parameters are given in Figure 3-3.

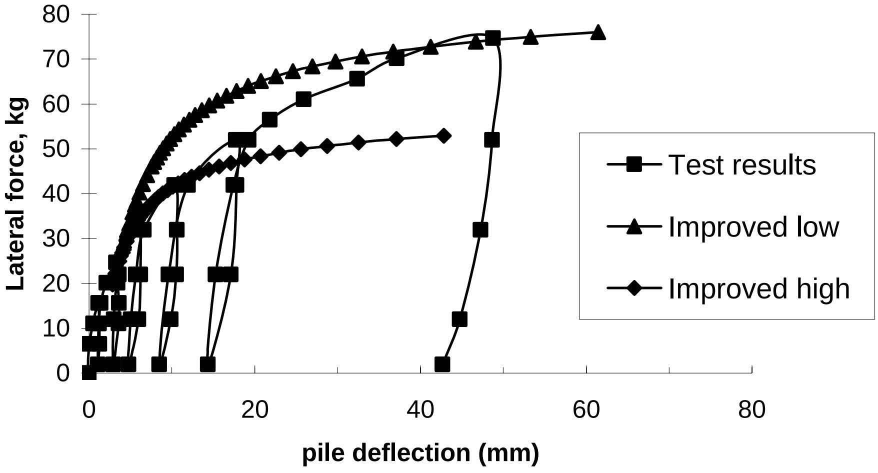

Figure 3-3: *Improved parameters.*

The bending moment, shear force, soil reaction, rotation and deflection are given in Figure 3-4 to Figure 3-8 for some chose load cases. The maximal lateral force applied is 74.7kg (733.5N) and the moment for this force is -112kNmm in a dept of 220mm. The dept for the maximal moment seams to be in the interval between 160mm and 240mm. The shear force has a minimal value of -476kN and a maximal of 270kN. The dept of the shear force equal to 0, seams to be in the interval of 180mm and 200mm. The deflection of the pile at the surface is measured to 48mm and the point of rotation is about 300mm below the soil surface.

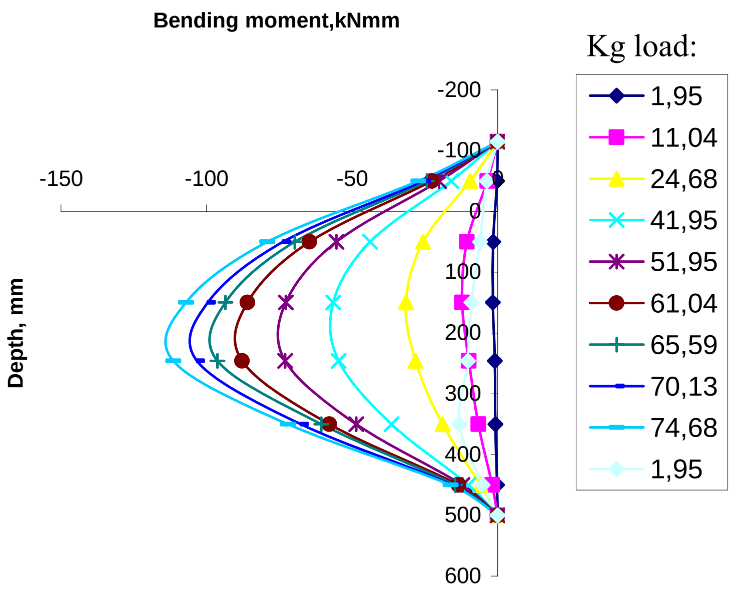

Figure 3-4: *Bending moment for static test.*

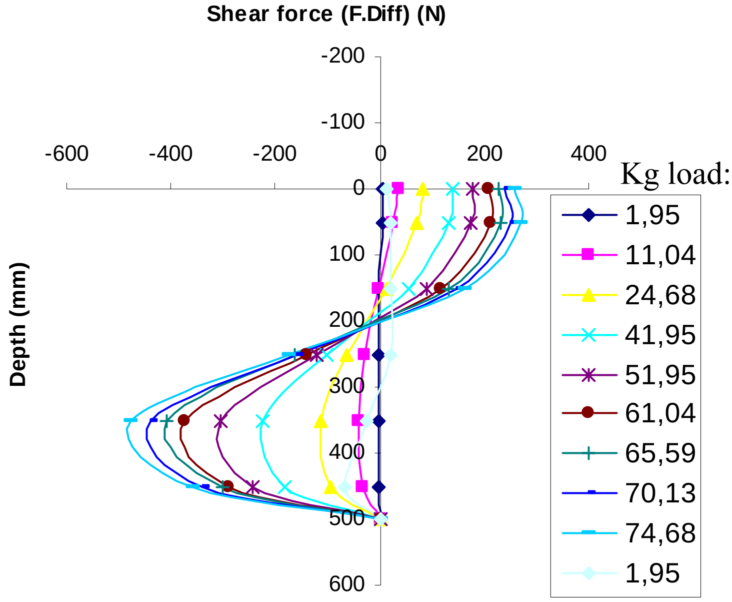

Figure 3-5: *Shear force for static test.*

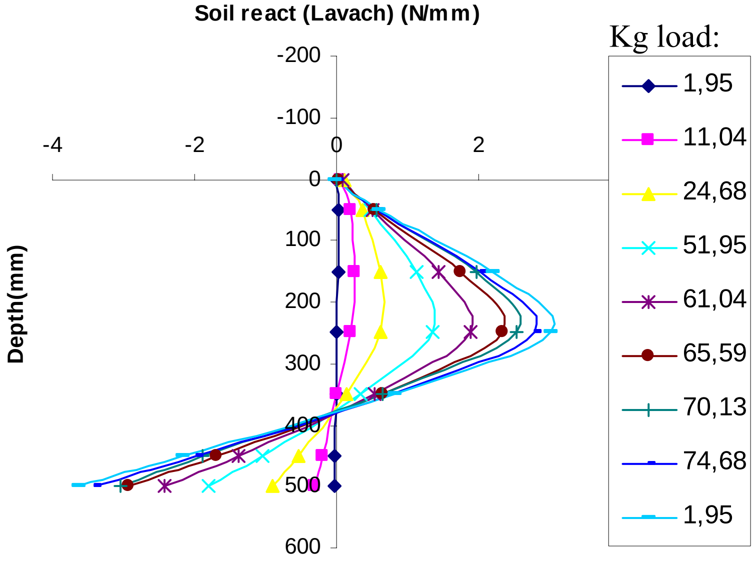

Figure 3-6: *Soil reaction for static test.*

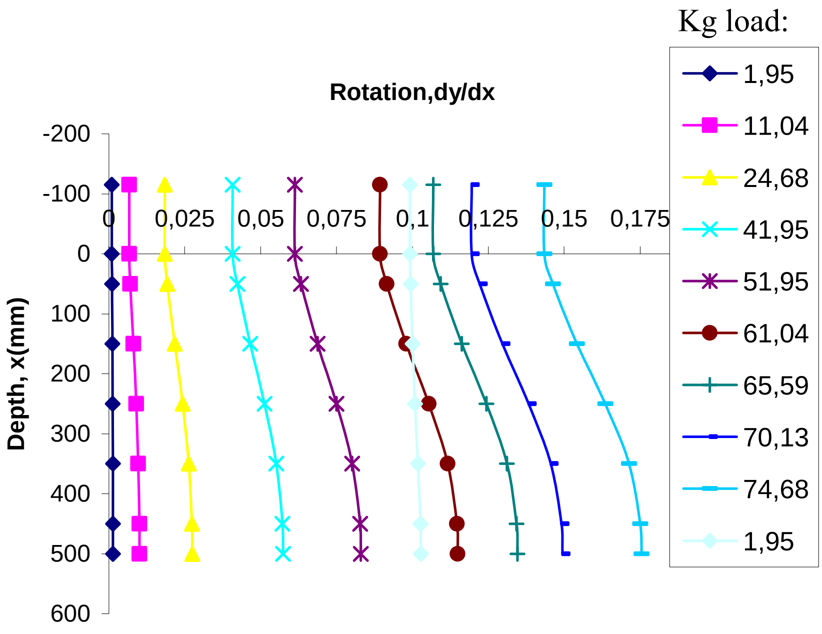

Figure 3-7: *Rotation for static test.*

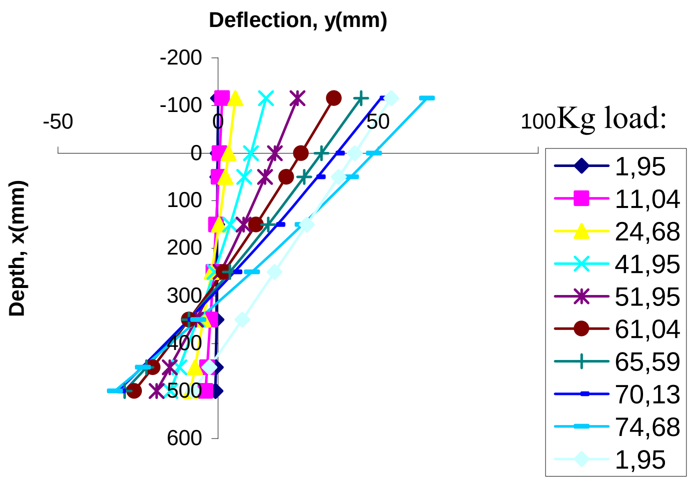

Figure 3-8: *Deflection static test.*

During the test, the sand flowed around the pile. This left a heave up in front the pile and a hole behind the pile. The hole behind the pile is measured and has a width of 120-130mm and a length of 130mm. The measuring is shown in Figure 3-9.

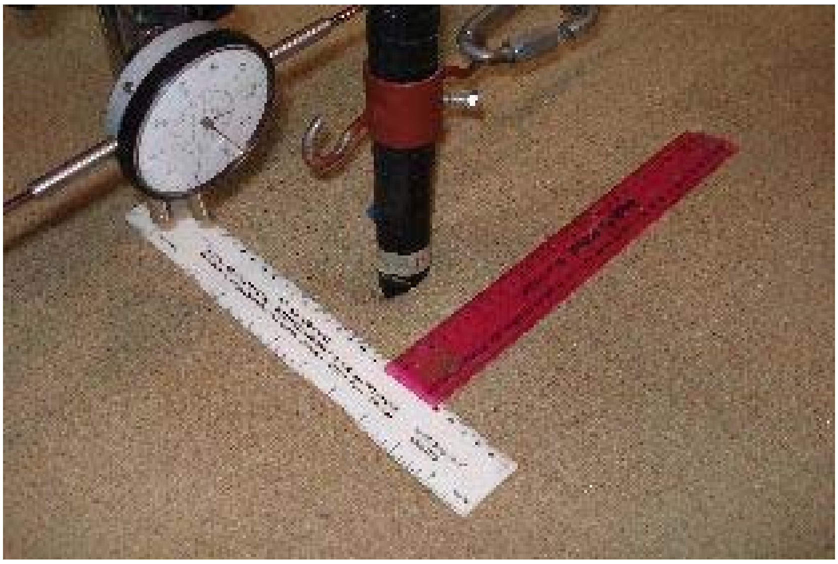

Figure 3-9: *Measuring of hole behind pile.*

3.2. Cyclic Loading 1 (L=1200mm, L_e=500, e=115mm)

The test program for the cyclic loading test 1 is 30 cycles with 11.95kg followed by 30 cycles with 21.95kg before during 50 cycles with 41.95kg and finally loading the pile to failure at 81.04kg (795.8N). The P-y curve is shown in Figure 3-10, fore some every 5th cycle. All cycles where continued till the deflection reached a point where it did not change much any more.

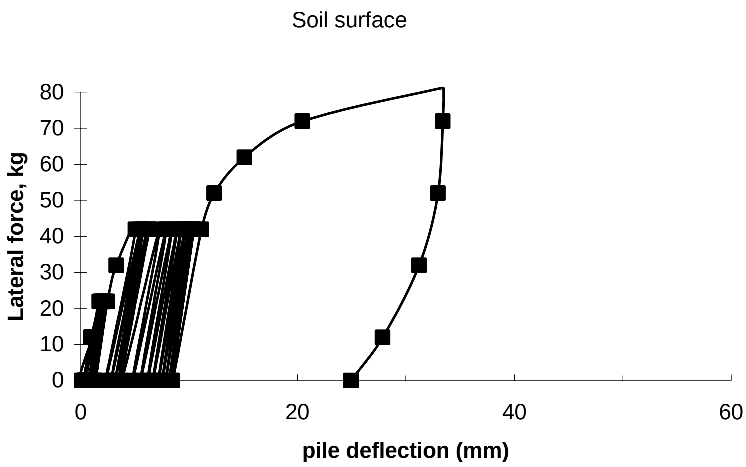

Figure 3-10: *P-y curve for cyclic test 1.*

Again, the closed form solution is used and the parameters are modified. The result is shown in Figure 3-11 and the parameters are given in Table 3.3 where the closed form solution is divided into a higher and lower value. The parameters that fits the test results best is in this interval.

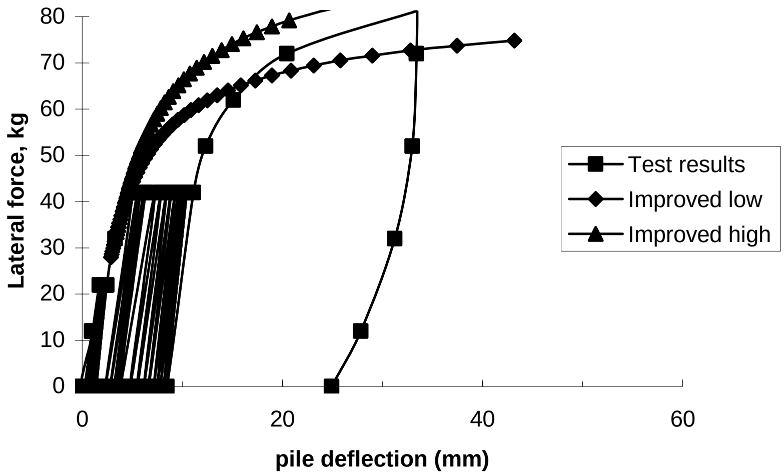

Figure 3-11: *Closed form solution.*

	Low	High
Ko	280,000 [kN/m^4]	280,000 [kN/m^4]
L	0.500 [m]	0.500 [m]
e	0.115[m]	0.115[m]
r0	0.016[m]	0.016[m]
γ	16.27[kN/m^3]	16.27[kN/m^3]
Kp	$\tan^2(45 + \varphi /2)$	$\tan^2(45 + \varphi /2)$
Ar	$\tan^2(45 + \psi/2)\gamma\ Kp^2$	$\tan^2(45 + \psi/2)\gamma\ Kp^2$
φ	38.5^o	38.5^o
ψ	10^o	15^o

Table 3.3: *Improved parameters.*

The results indicate that the cyclic loadings do not have a significant impact as long as the pile is loaded in the elastic area. However, when the pile is cycles loaded in the plastic area, 41.95kg, result in a huge deflection at about 8mm. Note that the cyclic loading with 41.95kg seams to harden the soil so that the soil afterwards has a elastic plastic response. The effect can be interpreted as a hardening equal to a larger load than the 41.95kg and a curve can be added so that the P-y curve gets the same shape as the non cyclic loaded P-y curve, cf. Figure 3-12.

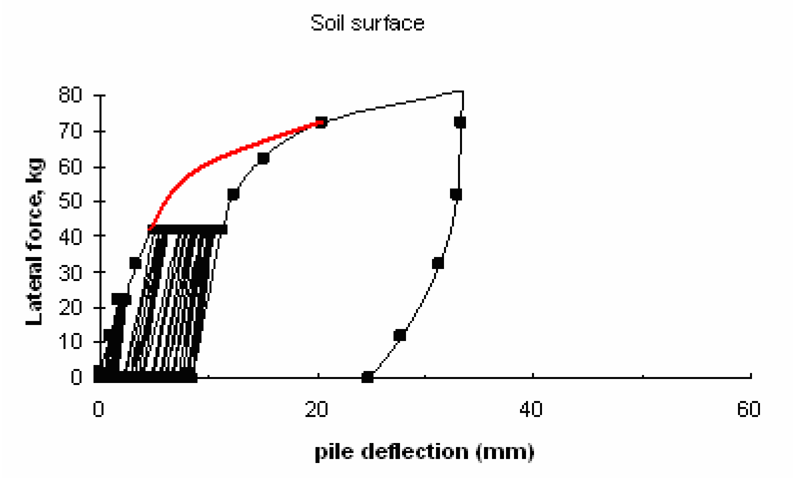

Figure 3-12: *Indication of non cyclic loading P-y curve.*

The Bending moment, shear force, soil reaction, rotation and deflection are shown in Figure 3-13 to Figure 3-17. The maximal moment at -175kNmm is obtained for the load at 81.04kg and the dept of the moment is 200mm. Furthermore, the maximal moment seams to be in the interval of 180mm and 200mm. The minimum value of the shear force is -750N in a dept of 350mm and the maximum shear force is 450N in a dept of 60mm. The interval of 0N shear force is about 180mm to 200mm. The maximal deflection is about 35mm and the rotation of the pile is in a dept of 250mm to 300mm.

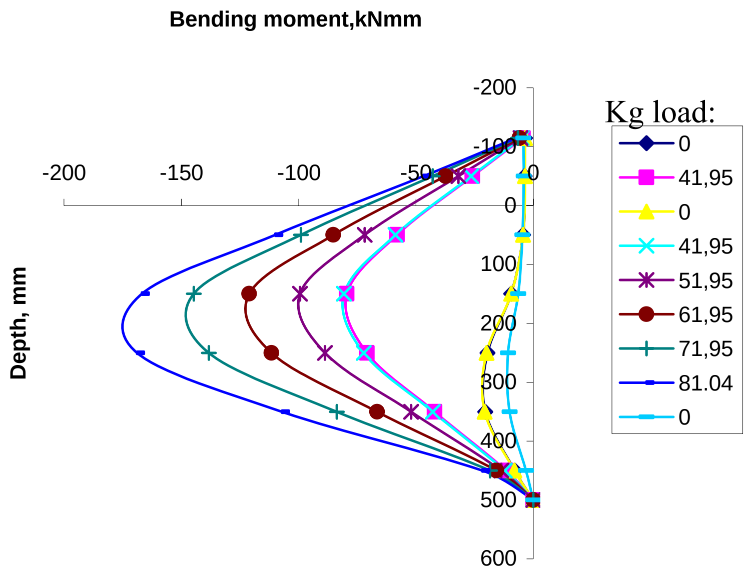

Figure 3-13: *Bending moment for cyclic test 1.*

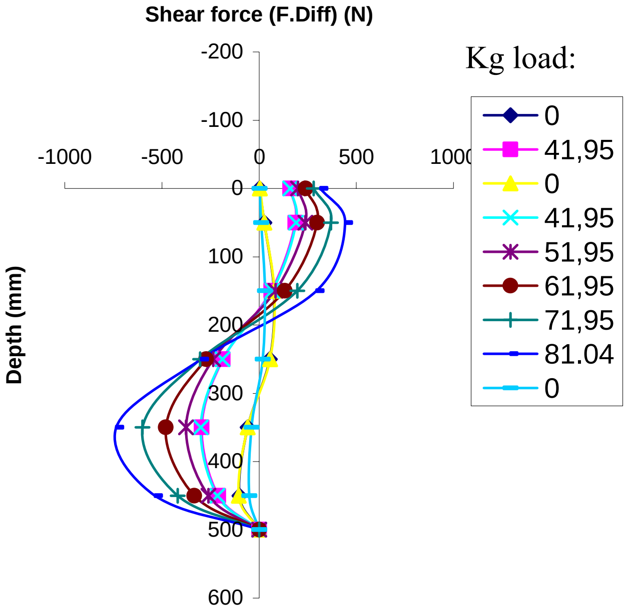

Figure 3-14: *Shear force for cyclic test 1.*

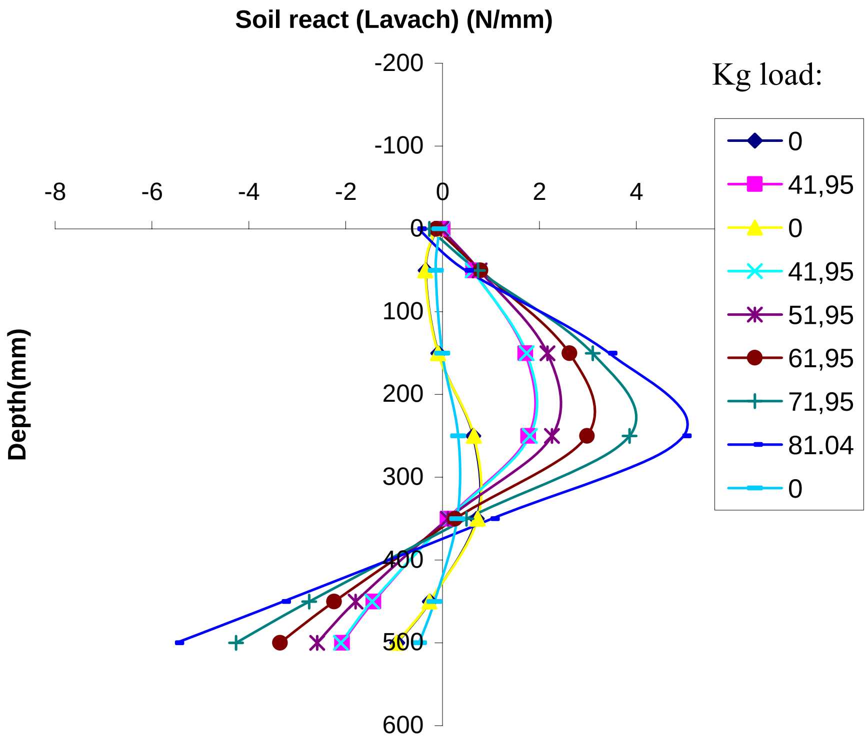

Figure 3-15: *Soil reaction for cyclic test 1.*

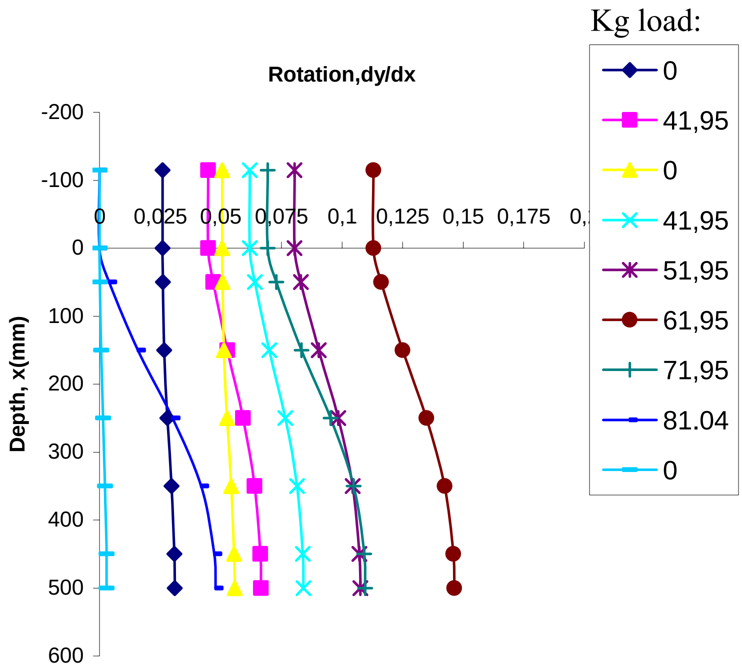

Figure 3-16: *Rotation for cyclic test 1.*

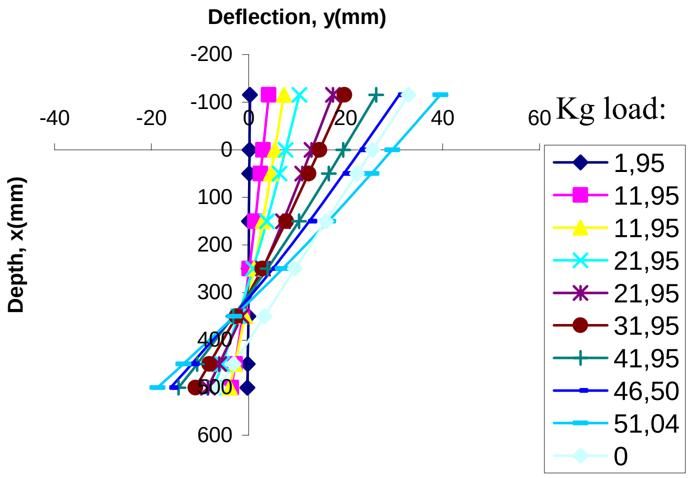

Figure 3-17: *Deflection for cyclic test 1.*

Because of a sand flow, there is created a heave in front of the pile and a hole behind is. The hole has a length of 115mm, a width of 125mm and a dept of 41mm.

3.3. Cyclic Loading 2 (L=1200mm, L_e=500, e=115mm)

The cyclic test 2 is preformed with reloading to 41.95kg and unloading to 21.95kg with 30 repetitions. After that a second load program with loading and unloading between 55.59kg and 41.95kg with 20 repetitions. Finally, the pile is loaded to failure which is 75.59kg. The P-y curve is given in Figure 3-18. The number of cycles is controlled of when the deflection has reached a stage of equilibrium meaning that it is the same in each cycle.

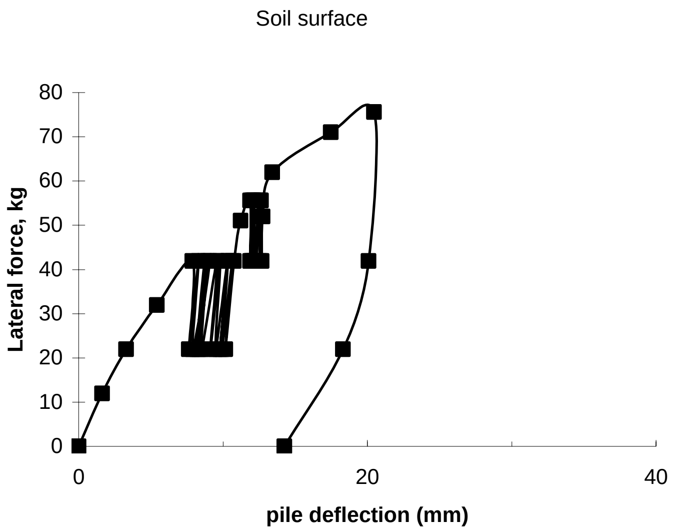

Figure 3-18: *P-y curve for cyclic test 2.*

The close form solution is used to verify the results. The parameters are for this case the same as for cyclic test 1 given in Table 3.3. The results are shown in Figure 3-19.

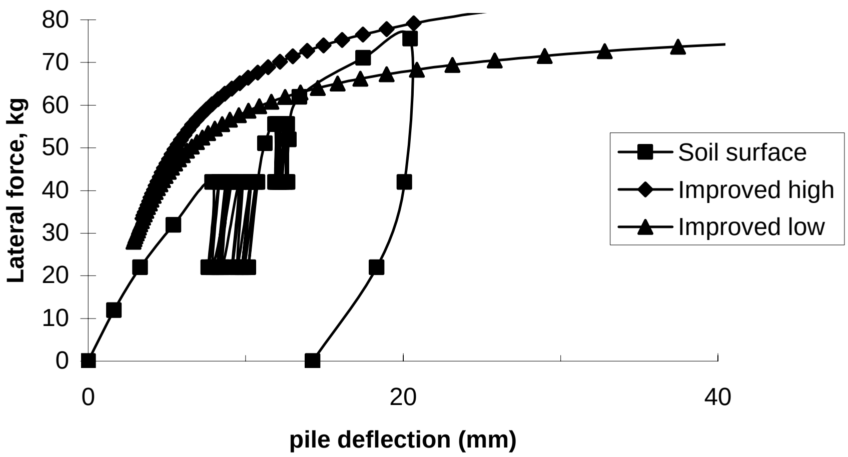

Figure 3-19: *Closed form solution.*

As in cyclic test 1, it seams as the effect of the cyclic loading is a hardening of the soil equal to a higher load. This means that the overall shape of the P-y curve is kept but due to the cyclic loading path is just lead another way, cf. Figure 3-20.

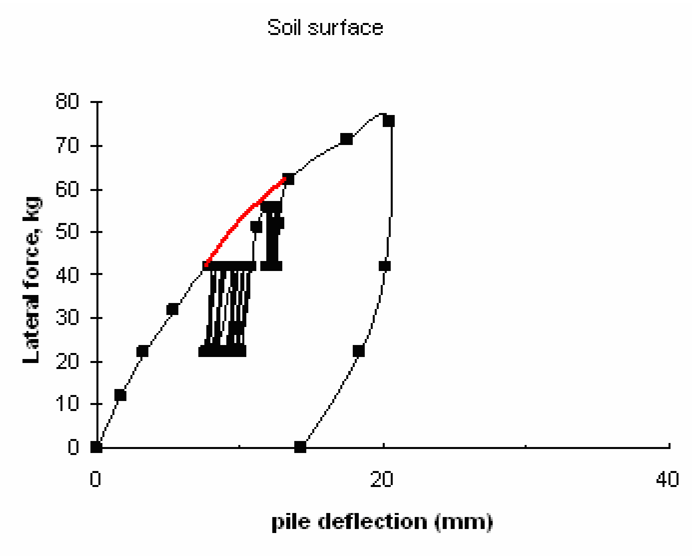

Figure 3-20: *Indication of non cyclic loading P-y cyrve.*

The bending moment, shear force, soil reaction, rotation and deflection are shown in Figure 3-21 to Figure 3-25 fore the some selected load step. The bending moment for the maximal load at 75.59kg is -85kNmm in a dept of 200mm. The maximal bending moment is in an interval of dept between 160mm and 220mm. The point where the shear force is equal to 0 is in an interval between 190mm and 230mm under the soil surface. This corresponds to the interval for the maximal moment. The minimal shear force is -335N and the maximal is 215N. The maximal pile deflection is 21mm at the soil surface and the point of rotation is between 220mm and 280mm.

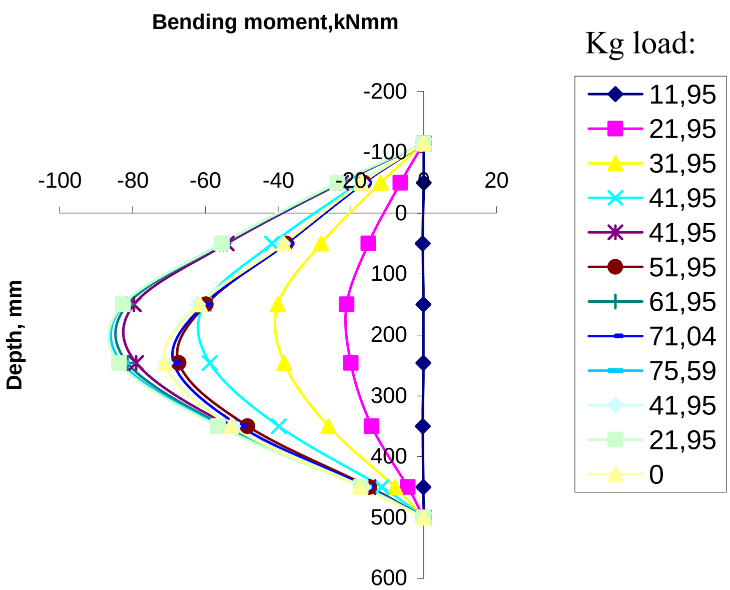

Figure 3-21: *Bending moment for cyclic test 2.*

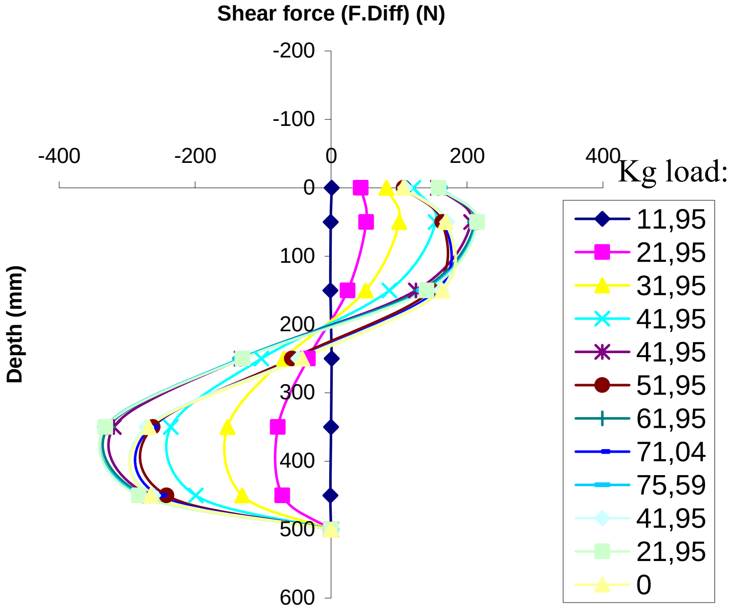

Figure 3-22: *Shear force for cyclic test 2.*

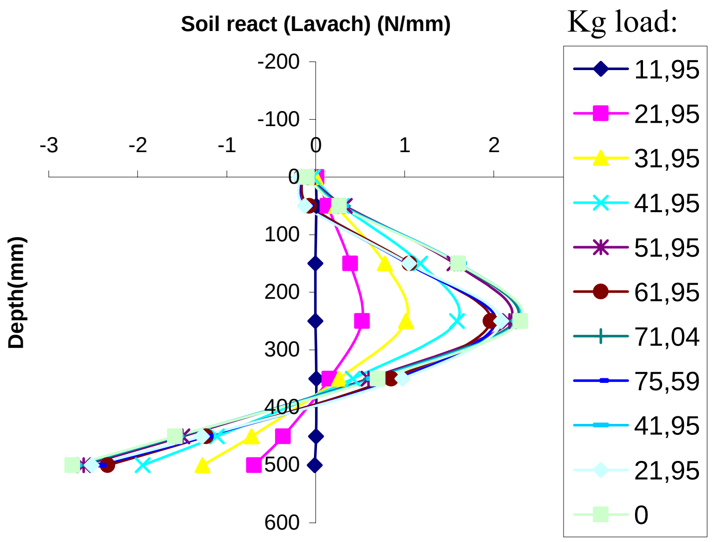

Figure 3-23: *Soil reaction for cyclic test 2.*

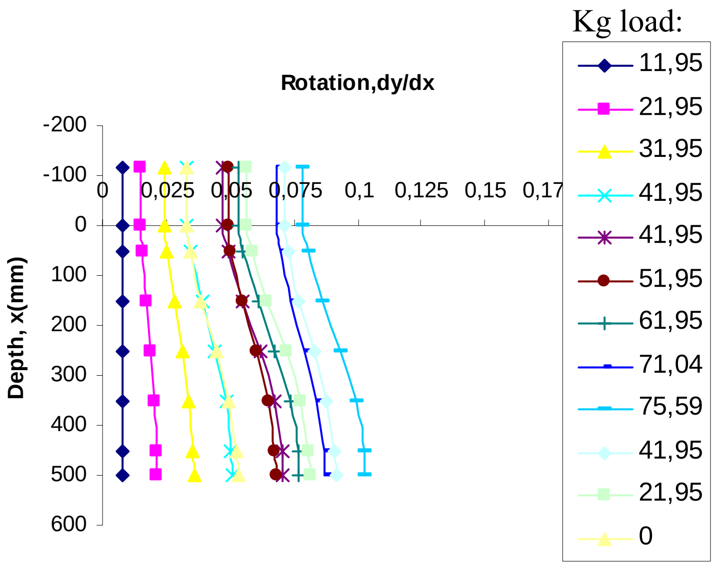

Figure 3-24: *Rotation for cyclic test 2.*

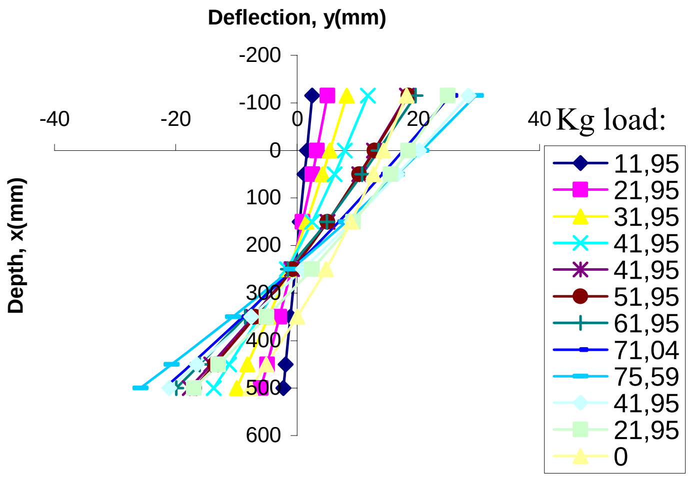

Figure 3-25: *Deflection for cyclic test 2.*

3.4. Cyclic Test 3 (L=1200mm, L_e=400, e=115mm)

In the cyclic test 3, the length of the pile is 400mm and the eccentricity is still 115mm. The loading program is 30 unloading reloading series with the load of 0kg to 11.95kg. The second series is also 30 cycles and the load is between 0kg and 21.95kg. After this, the pile is loaded to failure at 51,04kg, cf. Figure 3-26.

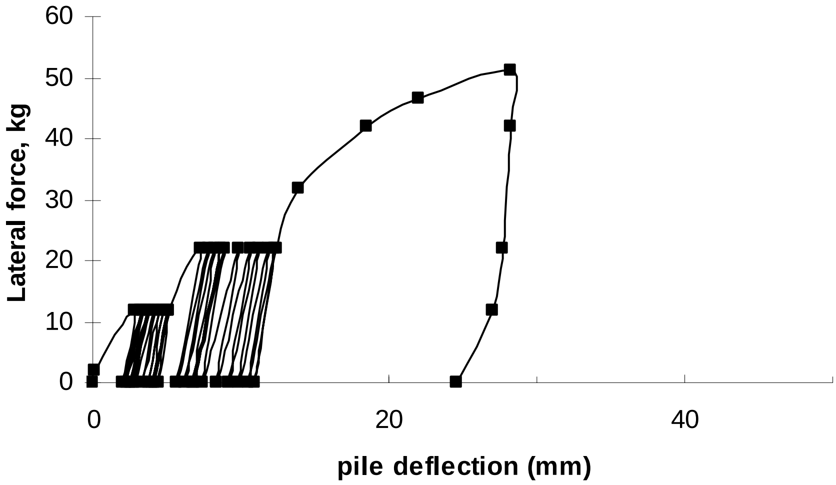

Figure 3-26: *P-y curve for cyclic test 3.*

The results are compared with the closed form solution in Figure 3-27 with the parameters in Table 3.4.

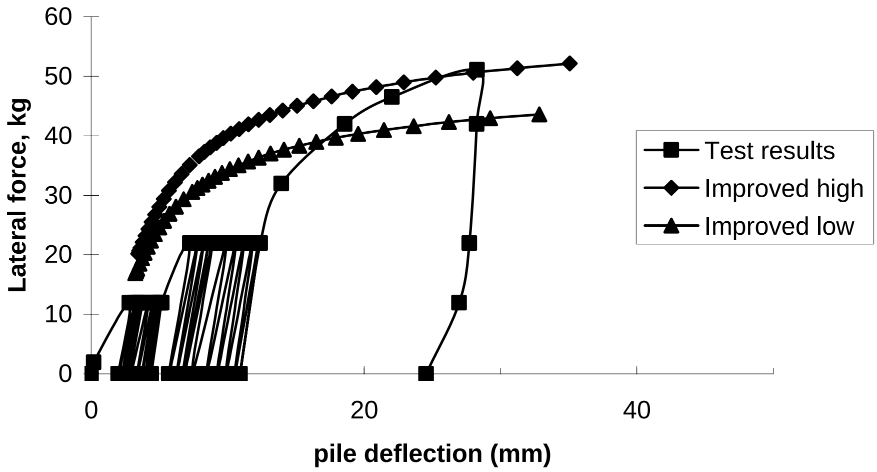

Figure 3-27: *Closed form solution.*

The only changed parameters compared with Table 3.3 are the K_0 and the length.

	Low	High
Ko	250,000 [kN/m^4]	280,000 [kN/m^4]
L	0.400 [m]	0.540 [m]
e	0.115[m]	0.115[m]
r0	0.016[m]	0.016[m]
γ	16.27[kN/m^3]	16.27[kN/m^3]
Kp	$\tan^2(45 + \varphi/2)$	$\tan^2(45 + \varphi/2)$

Ar	$\tan^2(45 + \psi/2)\gamma$ Kp^2	$\tan^2(45 + \psi/2)\gamma$ Kp^2
φ	38.5^o	38.5^o
ψ	10^o	15^o

Table 3.4: *Improved parameters.*

In order to verify the results, equation(.5) is used with the only difference L=400mm. The result is given by

$$P_u = \frac{0.5 \cdot 0.032 \cdot 0.4^3 \cdot 16.32 \cdot 16.27}{0.115 + 0.4} = 528N \qquad (.6)$$

This is equal to 54kg and is a bit higher than the measured 51.04kg in Figure 3-26. The reason is that the equation gives the ultimate plastic failure load which is not possible to obtain in reality.

The results from cyclic test 3 also suggest that the cyclic loading is equivalent to a higher non cyclic load, cf. Figure 3-28. The figure shows that when a higher load is applied after the cyclic loading the soil gives an elastic response equal to a load a third higher than the cyclic load. However, this depends on the amount of cyclic loads.

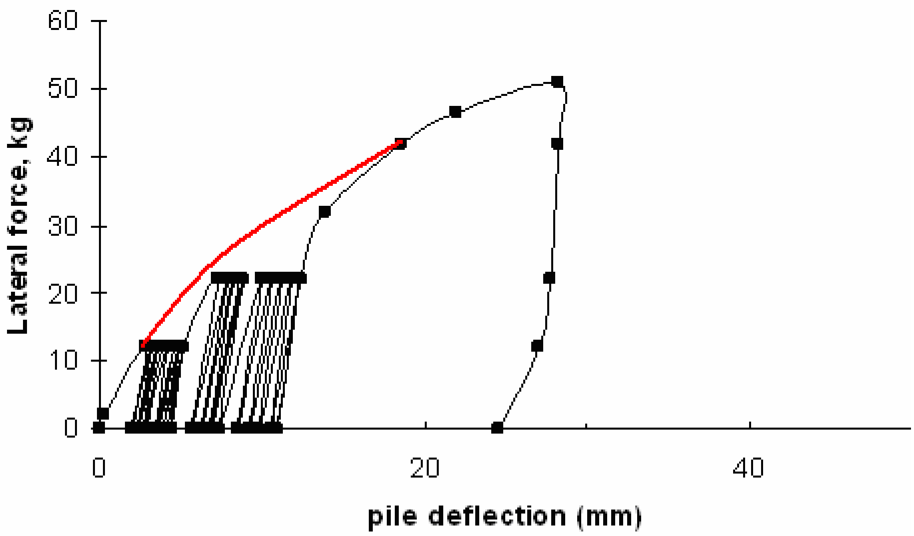

Figure 3-28: *Indication of non cyclic loading P-y cyrve.*

The bending moment, shear force, soil reaction, rotation and deflection are shown in Figure 3-29 to Figure 3-33. The maximal bending moment is measured to -86kNmm at the dept of 150mm. It seams as all the maximal bending moments is at the dept of 150mm. The minimal shear force is -460N and the maximal shear force is 260N. The point where the shear force is zero is at the depth of about 150mm for all results. This does correspond to the dept of the maximal bending moment. The maximal pile deflection is 21mm at the soil surface and the point of rotation is between 220mm and 250mm.

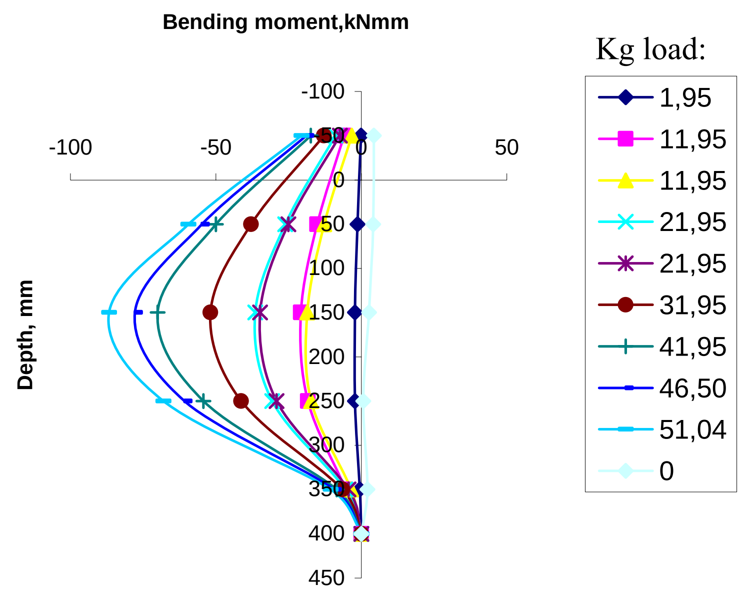

Figure 3-29: *Bending moment for cyclic test 3.*

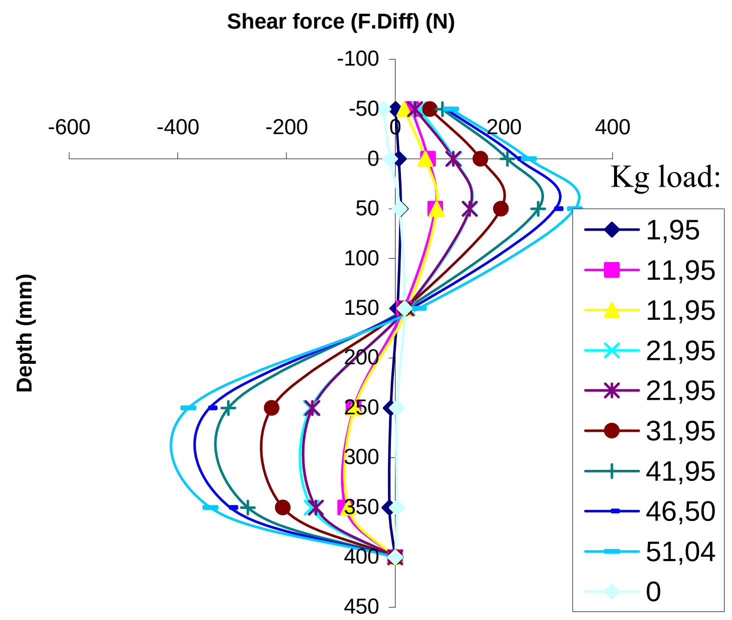

Figure 3-30: *Shear force for cyclic test 3.*

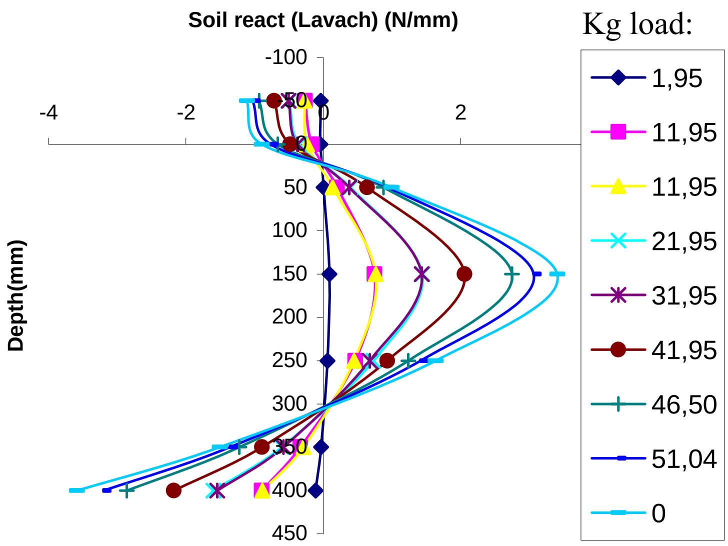

Figure 3-31: *Soil reaction for cyclic test 3.*

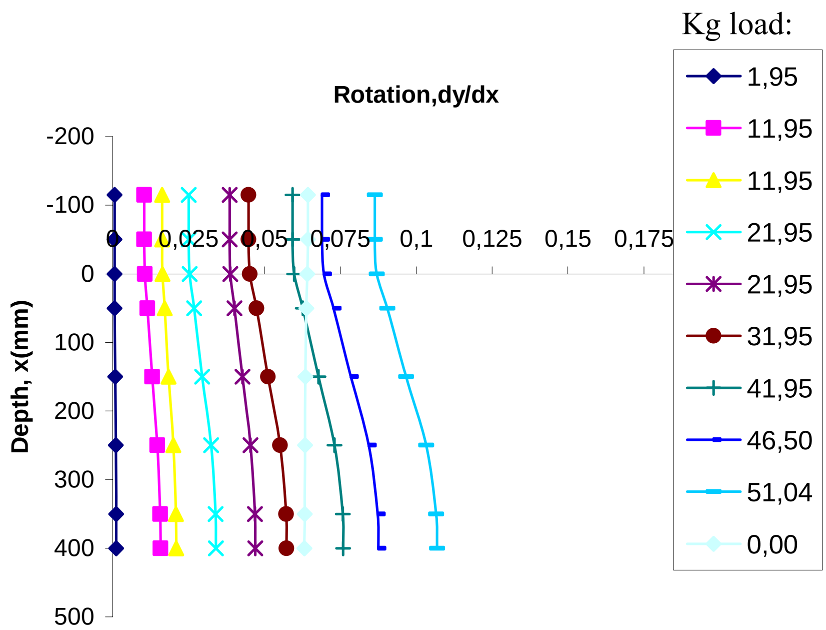

Figure 3-32: *Pile rotation for cyclic test 3.*

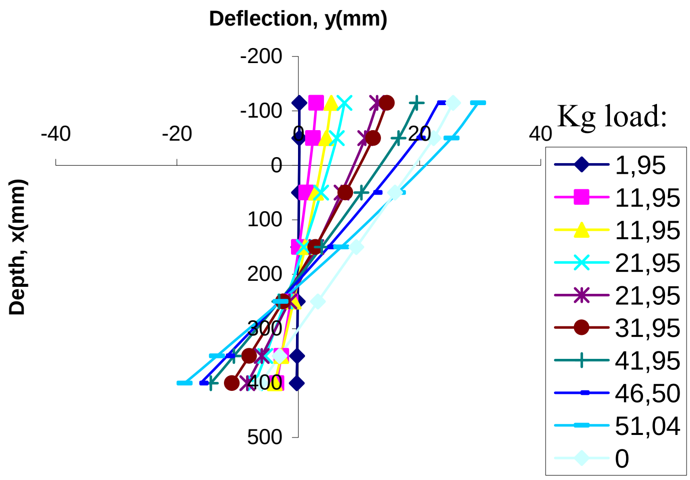

Figure 3-33: *Pile deflection for cyclic test 3.*

4. Discussion

The main results are summarized in Table 4.1.

Test no.	Failure load [N]	Depth of M_{max} [mm]	M_{max} [kNmm]	Min shear force [N]	Max pile deflection [mm]	Max soil reaction [N/mm] In layer L_m	In layer L_s
0	735	220	-112	-476	48	3	-3,8
1	796	200	-175	-750	35	5	-5,9
2	742	200	-85	-335	21	2,2	-2,5
3	501	150	-86	-460	21	3.4	-3.6

Table 4.1: *Main test results.*

For the pile length of 500mm, the results indicate that the depth of the maximum bending moment is 200mm. However, there is a big difference in the magnitude of the maximum moment varies much even though the load is about the same. This can be caused by that the results are determined by using the strain gage on the one side only since on gate broke on the other side. The pile was turned in different directions in the tests. Furthermore, the dummy strain gage increased its value through all tests. In order to estimate the effect of error in the strain gage due to the electrical heat, the maximal strain is compared to the strain in the dummy strain gage, cf. Table 4.2.

Test No	Strain in dummy gage	Maximal strain	Possible error %
0	39.4	1520	2.6
1	55.4	2304	2.4
2	95.0	2156	4.4

3	93,2	1535	6.1

Table 4.2: *Possible error in strain gage.*

The possible percentage error is less then 6% for all tests and that is not sufficient to yield the big difference in bending moment. Another reason is estimate to be that the pile has not been in line in all tests.

Looking at the P-y curve for the first 3 tests, it is seen that the soil response is harder in each test. This is probably because the same sand is used and it becomes denser after each test. This effect is hardening of the soil and the soil also hardens due to the cyclic loading.

Also the closed form solution suggests that the angle of friction is increasing, meaning that the soil is giving a harder response.

5. Conclusion

The purpose of this paper is to investigate the effect of one way lateral cyclic loading on piles in sand. This is done by performing one static test and 2 cyclic test on a pile embedded 500mm with an eccentricity of 115mm and one test with the pile embedded 400mm and the eccentricity of 115mm. The results suggest that the effect of the cyclic loading is equivalent to a higher static load. This means that the soil hardens due to the cyclic loading and after the cyclic the pile response elastic to a higher load than the cyclic load.

The failure load is compared to a simple equation for Gibson soil and the equation gives slightly too high loads. This is because it assumes that all the soil is in failure and that is not possible in reality but only in theory.

6. Acknowledgements

The author would like to thank Hongyu Qin for his help conduction the experiments.

7. References

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