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Set-up effects of piles in sand tested in the centrifuge

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ABSTRACT: The bearing capacity of piles increases over time. Research has shown that this is caused by an increase in shaft friction combined with a constant or only slightly increasing base capacity. Although there are some ideas on the mechanisms that play a role there is no quantitative model to describe this mechanism. From the literature the shaft friction seems to increase linearly with the logarithm of time. For piles in the field this is proven by load tests performed between 1 until approximately 1000 days after installation. Literature indicates that set-up as a function of time is also present minutes and hours after installation. This allows investigating the set-up mechanisms under controlled conditions in a centrifuge. Therefore two test series have been performed to investigate the set-up for a single pile and a pile group. This paper presents the relevant literature and describes the position of the tests in the on-going research program on piles in The Netherlands. Furthermore, the results will be described and discussed. Time dependency in bearing capacity in sand can be observed in the centrifuge tests, although it is not certain whether some of the increase has not been caused by other mechanisms. It appears that the testing conditions as well as the effects of installation of neighboring piles are of great importance on the time effects.

1 INTRODUCTION

1.1 *Evaluation of predicted pile capacity*

Research looking at the axial capacity of foundation piles (van Tol et al. 2010) has shown that calculating the capacity using the method set out in the Dutch standard (NEN 9997-1, 2012) results in a considerable overestimation of the capacity as compared to measurements in load tests. The study referred to properly equipped load tests conducted in France, Belgium and The Netherlands in which it was possible to distinguish between pile-base capacity and shaft capacity. The measured pile-base capacities of displacement piles proved on average to be only 70% of the predicted values. Piles located at a depth of more than 8*D* in the sand layer were found to have a pile base capacity of 60% of the predicted value (Stoevelaar et al. 2011).

Since the pile capacity calculation is too optimistic, and since no failures have been observed in practice, it is thought that there must be concealed safety factors in the system. The identification and quantification of those factors was investigated. The focus was among other aspects on the increase in capacity over time and group effects. This paper presents results of centrifuge modelling of time effects on the capacity of a single and a pile in a group.

1.2 *Increase of pile capacity in time*

Extensive research has been conducted into the increase of pile capacity over time. The shaft capacity of displacement piles in sand is often observed to increase with time, even after dissipation of installation-induced excess pore pressure—this phenomenon is known as pile set-up. Set-up rates of 20%–170% per log cycle of time and a capacity increase by a factor of 5 or more have been reported, and trend lines have been proposed

(Skov & Denver, 1988; Chow et al. 1997; Bullock et al. 2005). However, the governing mechanisms are not well understood. The magnitude of set-up is affected by many factors, i.e. pile diameter, pile penetration depth, soil friction angle and sand relative density (Alawneh et al. 2009). It is also suggested that ageing effects were related to the energy input during installation (Baxter, 1999). More violent soil disturbance results in greater ageing or capacity increase. Bowman & Soga (2005) show that fast loading to a high stress ratio in a triaxial test results in an earlier and greater dilatant creep response than for slower loading.

Skov & Denver (1988) proposed a method to estimate the long-term pile capacity (Q_t) in cohesive and cohesionless soils from the short-term pile capacity (Q_o) using the following correlation:

$$Q_t = Q_0 \cdot \left(1 + A \cdot \log_{10} \frac{t}{t_0}\right) \tag{1}$$

where:
t = time after the end of initial driving.
t_o = reference time elapsed since end of driving.
Q_o = pile capacity at time (t_o).
Q_t = pile capacity at time (t).

Skov & Denver recommended using A = 0.2 for piles in cohesionless soils. Chow et al. (1998) reported that, based on data collected from the work of 14 researchers, values of A vary from 0.25 to 0.75. Axelsson (1998) reported A-values from 0.2 to 0.8.

Before the positive effect of time can be included in the regulations, the effect must be further quantified and understood. Another important question is the extent to which the increase in capacity persists after varying loads have been imposed. Jardine et al. (2006) demonstrated that the repeated testing of piles in sand resulted in lower capacity measurements than tests on piles that have not been subjected to loads in the past.

Subsequent research will have to focus on quantification of the time effect, as well as the effects of varying loads. As such research in field tests is very time and cost consuming it is worthwhile to research the feasibility of capturing this time effect in a geotechnical centrifuge. It is generally thought that creep and relaxation processes, the supposed underlying mechanisms of set-up, cannot be modelled in a centrifuge because time does not scale. However according to Bullock (2005) Equation 1 also describes the set up directly after driving. Other observations regarding short term effects are that sometimes a delay is observed in the commencement of setup, (Axelsson, 2000; White & Zhao, 2006). The question whether in geotechnical centrifuge tests the time dependent aspects of the bearing capacity of piles can be detected is relevant.

In the literature, long-term set-up of piles in sand is, generally speaking, attributed to two main time-dependent causes, (Schmertmann, 1991 and Axelsson 2000):

1. Stress relaxation (creep) in the surrounding soil arch, which leads to an increase in horizontal effective stress acting against the pile shaft, i.e. long-term changes in the stress regime surrounding the piles influence set-up magnitudes.
2. Stress relaxation leading to an increase in dilatancy and stiffness of the soil, which implies larger horizontal effective stresses acting against the shaft during loading.

Both these mechanisms start directly after pile installation and are, to a certain degree, also a part of the short-term set-up that takes place during the dissipation of excess pore pressures (Axelsson, 1998).

These observations show that the installation method plays an important role in the set up and should therefore be modelled in the centrifuge as properly as possible. Another important aspect is the driving of neighbouring piles. This could have a significant effect on the degree of set-up as it may cause a sudden breakdown of the soil arch (Axelsson 2000).

This paper describes two series of geotechnical centrifuge tests that aim to capture the time effects.

2 TESTING OF SET UP EFFECTS

2.1 *Test arrangement*

The centrifuge tests focus primarily on the question whether the time dependency of pile capacity can be studied in the centrifuge. As creep and relaxation processes do not speed up with an increasing g-level, relatively long lasting centrifuge tests were run. If it appears to be possible to assess factor A in Equation 1, research can be conducted in the centrifuge, precluding the need for more expensive, long lasting field tests and allowing controlled conditions. Assuming that Equation 1 describes the time dependent pile capacity correctly these centrifuge tests can predict this long term capacity.

The test set-up is shown in Figure 1. Two instrumented test piles are installed in a single soil sample prepared in the container, one single pile and a pile in a group of 3 piles. The forces on the pile head and base of the instrumented piles could be measured separately. The two test piles and the other piles in the group are installed in flight. To study the time effect of pile 1, load tests were planned at

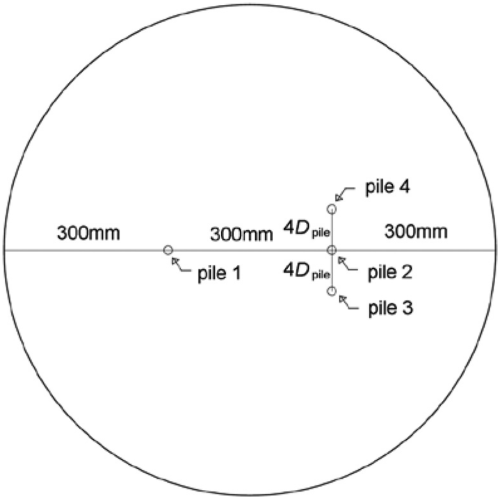

Figure 1. Centrifuge test design, test piles diameter 16 mm; container diameter 900 mm. Piles 1 and 2 are the test piles, pile 3 and 4 dummy piles.

Table 1. Baskarp sand characteristics.

Parameter	
Density grains	2.65 [kg/m^3]
D_{50}	118 [µm]
D_{60}/D_{10}	1.4
n_{min}	35.2%
n_{max}	47.6%

1, 10, 100 and 1000 minutes after installation. Then pile 2 has been loaded, in series 1 after installation of both neighbouring piles. In series 2, pile 2 was installed after pile 3 and load tested, next pile 4 was installed and pile 2 was load tested again. Detailed time schedules are given in Tables 2 and 3. The centrifuge continued spinning from the start of the installation until the final load test.

2.2 *Test programme*

The tests were run in the geotechnical centrifuge of Deltares. As pile installation and group effects are an important issue in regard of set-up, driven, jacked, single and group piles have been tested.

The tests were performed at 40 g. The diameter of the steel pile D_p is 16 mm (A_{base} = 200 mm^2). The penetration in the sand is approximately 320 mm (20D_p). The total height of soil body is 600 mm, the diameter of the container is 900 mm; the distance from pile to wall 300 mm (18D_p). The distance from the single pile to group is 300 mm. The distance between piles in group (centre-to-centre) is 64 mm (4D_p).

Table 2. Test scheme for single pile 1, series 1.

Activity	Velocity (mm/s)	Duration (min)	Time line (min)
Start		–	0
Cyclic installation over 320 mm	1	5.33	5
Waiting for 1 min		1	6
Capacity test (10%D_p)	0.002	14	20
Waiting for 10 min		10	30
Capacity test (10%D_p)	0.002	14	44
Waiting for 100 min		61	105
Capacity test (10%D_p)	0.002	14	119
Waiting for 1000 min		1141	1260
Capacity test (10%D_p)	0.002	1	1274
Waiting for other test		15	1289
Load at 50% and cyclic displ. (0.1 mm)	0.05–0.05 cos2πt/1.2	1	1290
Capacity test (10%D_p)	0.002	14	1304

The tests were performed with totally rough interfaces: the normalized roughness R_n = 0.27 and R_{max} = 32 µm. The suitable roughness was obtained by a fine screw thread along the entire shaft surface.

Baskarp sand was used with a D_{50} of 0.118 mm. The D_p/D_{50} ratio is 135, which fulfils the minimum100 requirement for scaling (Garnier & König, 1998). The sand was prepared by dynamic compaction of a fully saturated sample (see Rietdijk et al. 2010) at a relative density D_r of respectively 66.3% and 66.8% in series 1 and 2. The Baskarp characteristics are depicted in Table 1.

2.3 *Installation of the model piles*

The installation of the model piles into the sand mass was displacement controlled. The aim was to simulate a 'real' pile-driving signal (hammer blows with rebound) to install pile 1. The group piles were jacked into the sand with constant velocity. The installation velocity for the pseudo driven pile was a penetration rate of 1.2 mm/blow. To simulate the driving process, a rebound amplitude of 2%D_p (0.32 mm) and 3%D_p was chosen in the first test series respectively in the second test series. This upward movement of the pile was assumed to be sufficient to change the direction of the shear strain in the soil around the pile. In earlier research on cyclic installation of model piles in a centrifuge (Stoevelaar et al. 2011) a rebound of 1%D_p was applied (at 40*g*). The force at the head dropped to about 0.4F_{max}. In another run (80*g*), a rebound of

Table 3. Test scheme of pile in group, series 1.

Activity	Velocity (mm/s)	Duration (min)	Time line (min)
Start			0 (150)
Static installation of centre pile (315.2 mm)	1	5.25	5 (155)
Waiting for 1 min		1	6 (156)
Capacity test (10%D_p)	0.002	14	20 (170)
Waiting for 10 min		10	30 (180)
Capacity test (10%D_p)	0.002	14	44 (194)
Waiting for 100 min		61	105 (255)
Capacity test (10%D_p)	0.002	14	119 (269)
Static installation of outer piles over 320 mm	1	5.33	124 (274)
Waiting for 1 min		1	125 (275)
Capacity test (10%D_p)	0.002	14	139 (289)
Waiting for 10 min		10	149 (299)
Capacity test (10%D_p)	0.002	14	163 (313)
Waiting for 100 min		61	224 (374)
Capacity test (10%D_p)	0.002	14	238 (388)
Waiting for 1000 min		887	1125 (1275)
Capacity test (10%D_p)	0.002	14	1139 (1289)
Waiting for cyclic displacements and testing of the single pile		15	1154 (1304)
Load at 50%, cyclic displacements (0.1 mm)	0.05–0.05* cos2πt/1.2	1	1155 (1305)
Capacity test (10%D_p)	0.002	14	1169 (1319)

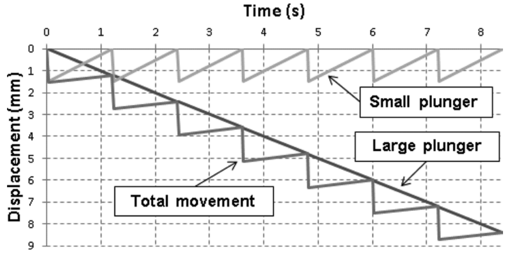

Figure 2. Induced displacement according to a triangular signal to simulate the driving process (theoretical).

5%D_p was supplied and the force at the pile head became zero.

Two options have been explored to obtain a realistic pile-driving signal for the single pile. A sinusoidal and a triangular signal were compared. The sinusoidal signal is too even for simulating the blow, therefore a triangular signal is chosen, see Figure 2.

2.4 *Test scheme*

The test scheme of the first test series is shown in Table 2 for the single pile and Table 3 for the pile in the group.

The pile load tests were performed at a displacement rate of 0.002 mm/s up to a pile head displacement of 10% of the pile diameter and lasted 14 min. This hampered the intended pile load test after 10 min. The test on the single pile lasted nearly 22 h. The test on the pile in the group started 2.5 h after the start of the single pile. The test scheme of series 2 was similar. In series 2, the load tests on the instrumented piles at 10 minutes after installation were cancelled: it was thought that these tests caused too much disturbance.

Also larger displacements were applied for testing: 20%*D* and the piles of the group were installed in a different order (in test series 2, pile 3 was already installed before installing pile 2). Pile 2 was first tested subsequently up to 1000 min before pile 4 was installed. However, due to problems with the centrifuge, pile 2 could not be tested at 1000 min after installation of pile 4.

3 TEST RESULTS

All test results are presented in model scale. The forces on the pile head and pile base measured during installation of pile 1 in series 1 and 2 are plotted in Figure 3. The penetration forces in series 1 are linear with depth, while in series 2 there is a change in slope after about 10D_p penetration.

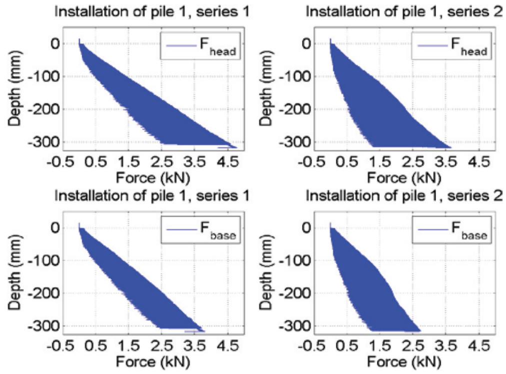

Figure 3. Installation of pile 1 in series 1 and 2.

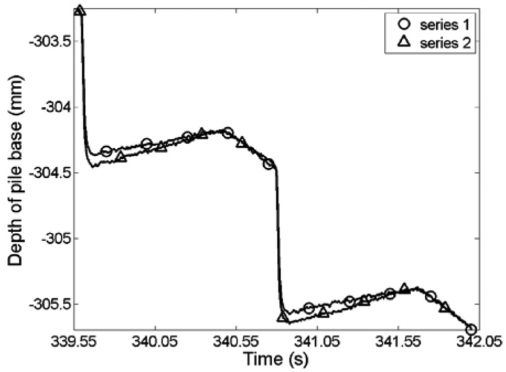

Figure 4. Two "strokes" during installation of pile 1.

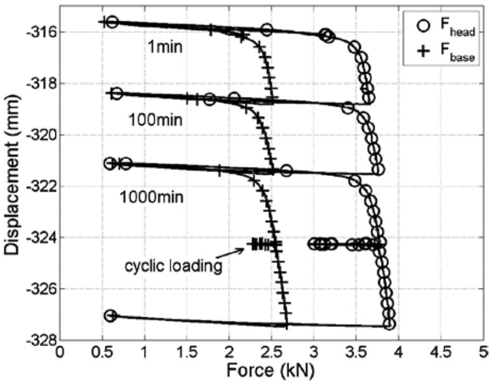

Figure 5. Load test on (driven) pile 1 in series 2.

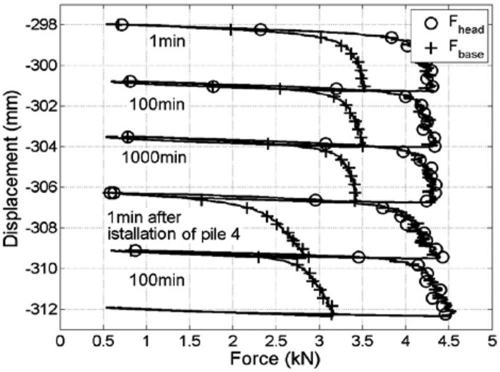

Figure 6. Load test on (jacked) pile 2 in series 2.

This difference is dominated by the response of the pile base (lower part of Fig. 3). It can be observed that there was more unloading of the pile base during installation in series 2, due to a slightly larger amplitude during installation. Figure 4 shows the time penetration process (two blows) of the driven pile 1 in series 1 and 2.

Figure 5 shows the results of the load tests on (driven) pile 1 in series 2. There is a slight increase in time of the total pile capacity, while the base capacity does not increase at all.

Figure 6 shows the results of the jacked pile in series 2. This pile was jacked, after pile 3 was installed, leading to a somewhat higher penetration force as a result of the installation of pile 3. It appears that the total capacity in time does not increase, but at the installation of adjacent pile 4 there is a direct strong reaction of pile 2: the base capacity decreased substantially and as the total capacity remains approximately constant the shaft capacity has increased, which agrees with Chow's (1995) findings. The subsequent load test after 100 minutes shows a regain of base capacity and a small increase of total capacity. Apparently a redistribution of the loads occurs.

Most authors find that set up effects of piles are attributed to the increase of the shaft capacity rather than to the base capacity (Axelsson, 2000; White & Zhao, 2006). The shaft resistances based on the difference between total and base capacity of pile 1 in test series 1 and 2 are depicted in Figure 7. The total shaft capacity is transferred to total friction (dividing by the total surface area) and normalized by the mean vertical effective stress along the pile. Pile 1 in series 1 shows a considerable increase in shaft capacity between 100 and 1000 min.

Pile 1 in series 2, installed with a higher rebound shows the increase between 1 and 100 minutes. In both cases the shaft capacity decreases after cyclic loading, but stays higher then the initial capacity.

Figure 8 shows the development in time of the normalized shaft capacity of pile 2, the jacked pile, in series 1. In series 1 there is a considerable

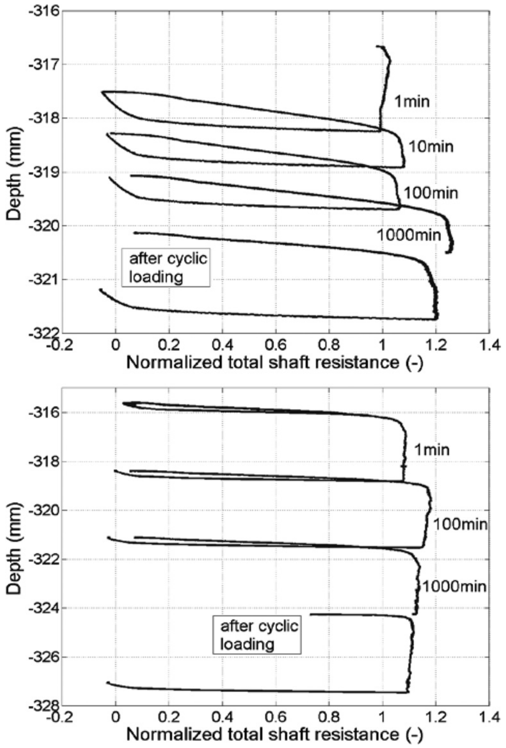

Figure 7. Shaft capacity of pile 1 in series 1 (top) and 2 (bottom).

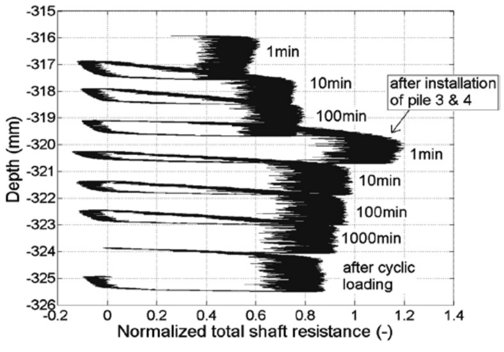

Figure 8. Shaft capacity of pile 2 in series 1.

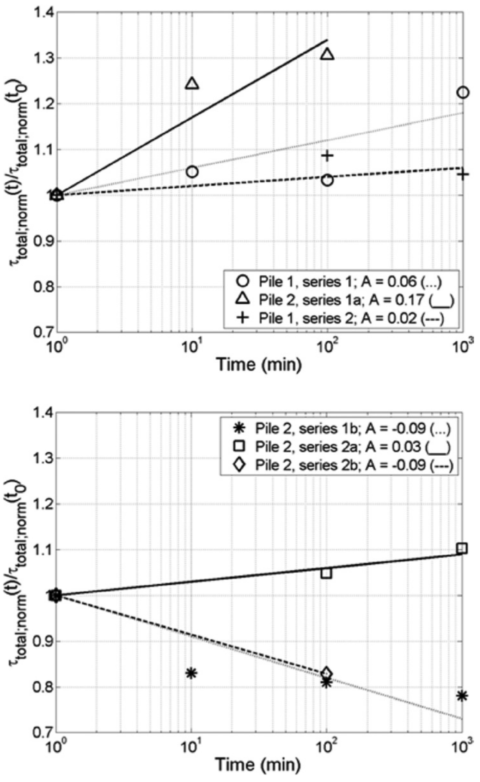

Figure 9. Ratio of total capacity at time t over the capacity at t_0 as a function of the time, for the single pile (top) and the pile in the group (bottom).

increase in capacity from 1 to 10 minutes and a further 50% of increase due to the installation of the two neighbouring piles. This last increase is partly lost in time but after 100 minutes there is still an increase relative to the shaft capacity at that time prior to the installation of the neighbouring piles. Again it appears that after the cyclic loading the gain in capacity is partly lost. The pile in the group in series 2 demonstrates a similar behaviour and is not shown in the paper. In Figure 9 the ratio of total capacity at time t over the capacity at t_0 is presented as a function of the time at log scale for the single pile (top) and the pile in the group after the installation of the neighbouring piles (bottom). The slope of the line presents the A-value in Equation 1. For the single piles the A-values ranges form less then 0.05 up to 0.15. The data for pile 2 in Figure 9 (top) count for the measured data before installation of the neighbouring pile. For group piles the A-values after installation of the neighbouring piles are negative.

Figure 10 shows the base capacity ratio in time for the single piles. It can be seen that the ratio is zero in series 2, which is in agreement with literature findings (Axelsson 2000). The negative A-values for the base in series 1 are presumably the result of the excessive unloading after the load tests in series 1, see Figure 7 top relative to series 2, Figure 7 bottom. It is believed that the strong unloading resulted in almost zero base stress after the unloading and therefore a reduction of base capacity in time.

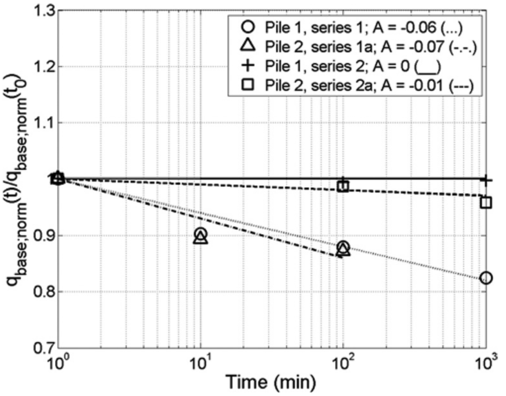

Figure 10. Ratio of base capacity at time t over the capacity at t_0 as a function of the time, for the single piles.

4 CONCLUSIONS

The objective of this research was to investigate the feasibility of assessing the set up effects of piles in centrifuge testing.

In the tests carried out the time effect has been tested under a variety of conditions, such as jacked and driven installation, single pile and a pile in a group. In all the tests time effects in the bearing capacity have been observed. It can therefore be concluded that set up of piles can be studied in a centrifuge. Quantifying these effects requires a large number of well defined test series with unique and repeatable conditions, preferably with testing over time of virgin (not previously loaded) piles, as the testing itself may affect the pile capacity.

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