Rapid pile load tests in the geotechnical centrifuge

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ABSTRACT: Centrifuge experiments were carried out to gain insight into the factors that affect the mobilized resistance during rapid load testing on piles in sand. The influence of generated pore water pressure during rapid load tests is studied, and its effect on the commonly used unloading point method to derive the static pile capacity. This paper describes the testing program and the test set-up. Typical measurement results from 36 rapid- and 12 static load tests are presented. The effects of the loading rate and excess pore pressures on the pile resistance are shown. The tests confirm that a rapid load test can overestimate the static capacity due to pore water pressure, for piles in medium to fine sands. The results of the pore pressure measurements show a combination of positive and negative excess pore pressure in the zone around the pile base, which can be explained by compression, volumetric behavior during shearing and pore fluid flow around the pile.

1 INTRODUCTION

Rapid pile load test (RLT) methods such as the Statnamic test (Birmingham & Janes, 1989 and Middendorp et al., 1992), the pseudo-static pile load tester (Schellingerhout & Revoort, 1996), or the spring hammer rapid load test method (Matsuzawa et al., 2008) are considered to be efficient alternative methods for static pile load testing (SLT). To improve the usefulness of the test, uncertainties regarding the assessment of the derived static capacity must be clarified. One of such uncertainty is the effect of generated excess pore pressure. During the rapid load test, excess pore water pressure is generated in the soil close to the pile, even when located in sand (Hölscher, 1995 and Maeda, 1998). How this excess pore pressure affects the equivalent static stiffness and the ultimate bearing capacity of the pile is not well known.

The most common method to derive an equivalent static pile capacity from a rapid test is the unloading point method (UPM), see (Middendorp et al, 1992). This method takes into account the soil viscous damping and the pile inertia, but not the effect of pore pressure. According to McVay et al, (2003), the rapid load test, interpreted by the UPM, overestimates the ultimate static capacity of piles in sand by an average of 10%. Analysis of more recent tests Hölscher, et al (2009) confirmed the findings of McVay et al. Nevertheless, the UPM provides a good correlation with static load tests for piles in sand and gravel (Brown, 1994; McVay et al, 2003).

This paper studies the effect of excess pore pressure by performing a number of rapid load tests on piles in sand in a geotechnical centrifuge. A geotechnical centrifuge is a suitable equipment to carry out scale tests which requires proper scaling of the stress with depth. Since the strength of sand depends on stress, scale tests on sand must be carried out in a centrifuge. If the test is scaled with a factor N, the acceleration must be increased with a factor N to reach stress identity. Consequently, also the time must be scaled with a factor N, i.e. time runs faster..

The objective of the tests presented in this paper is to determine whether the excess pore pressure is indeed responsible for the aforementioned 10% overestimate of the static capacity. If so, and if the effect can be predicted, then it offers the possibility of calculating the equivalent static pile capacity from an RLT more accurately.

Some centrifuge experiments described in literature are relevant to the topic of non-static pile load testing in a centrifuge (Allard, 1990; de Nicola and Randolph, 1994; Bruno and Randolph, 1999). These tests focused on the behavior of piles or surrounding sand during a dynamic pile load test, but none adequately considered the pore pressure

response. Allard (1990) performed the experiments in dry sand. De Nicola and Randolph (1994) and Bruno and Randolph (1999) used oil-saturated silica flour, to "scale correctly the pore pressure generation and dissipation during the installation". They focused on pile driving and dynamic testing, without measuring the excess pore pressure in the soil.

2 SCALING DRAINAGE CONDITIONS DURING THE RAPID TESTS IN SAND

Huy et al (2007) have indicated that the effect of excess pore pressure in a rapid load test can be expressed by a dimensionless factor η, originally suggested by Hölscher and Barends (1992). This so-called dynamic drainage factor is defined as:

$$\eta = \frac{GT}{g\rho R^2}k \quad = \frac{GT}{\rho R^2}\frac{K}{\nu} \tag{1}$$

where G is the shear modulus [Pa], T the duration of the loading [s], ρ the water volumetric mass [kg/m^3], and R the pile radius [m] k the permeability of the sand [m/s] and g the acceleration due to gravity [m/s^2]. In the second part is K the intrinsic permeability of the san [m^2] and ν the dynamic viscosity [kg/sm].

If water is used in the centrifuge, tests scaled 1:N (so the acceleration in the centrifuge is N g), the drainage factor will be N times smaller than in the prototype, since time is scaled with 1/N and the radius with 1/N^2. If a fluid with N times higher viscosity is used, the drainage factor will be identical. Starting point was a scale test with N = 40.

The viscosity of the pore fluid was increased to a higher lever for two reasons:

- Due to limitations of the loading system the duration of loading was about 3 times longer then it should be based on the scaling rules
- By increasing the viscosity, the drainage is slower and the phenomenon of interest is more visible.

Since the viscous fluid had a viscosity of 300 times the viscosity of water, the drainage in the centrifuge was 300/40/3 = 2.5 times slower than it would be in prototype in this sand type.

3 EXPERIMENTAL SET-UP

Figure 1 shows the test set-up. The load tests were carried out in a 0.6 m-diameter and 0.79 m-high steel sand-filled container (sand height 0.46 m). The pile was installed by a slow hydraulic actuator with a large stroke and afterwards tested by a fast actuator with a much small stroke. The pile had diameter 11.3 mm, length 300 mm and mass 1.08 kg

Baskarp sand (Allard et al, 1994) with d_{50} = 130 μm was used. The sample was prepared according to the method of Van der Poel and Schenkeveld (1998). First, the sand was pluviated in water, then the sand was densified by dynamics and afterwards the sample was carefully saturated with viscous fluid. In the sand four pore fluid pressure transducers were installed.

Table 1 shows the properties of the samples in the three tests discussed in this paper. Test 1 was a pilot test. After the pilot significant changes in test set-up had been introduced.

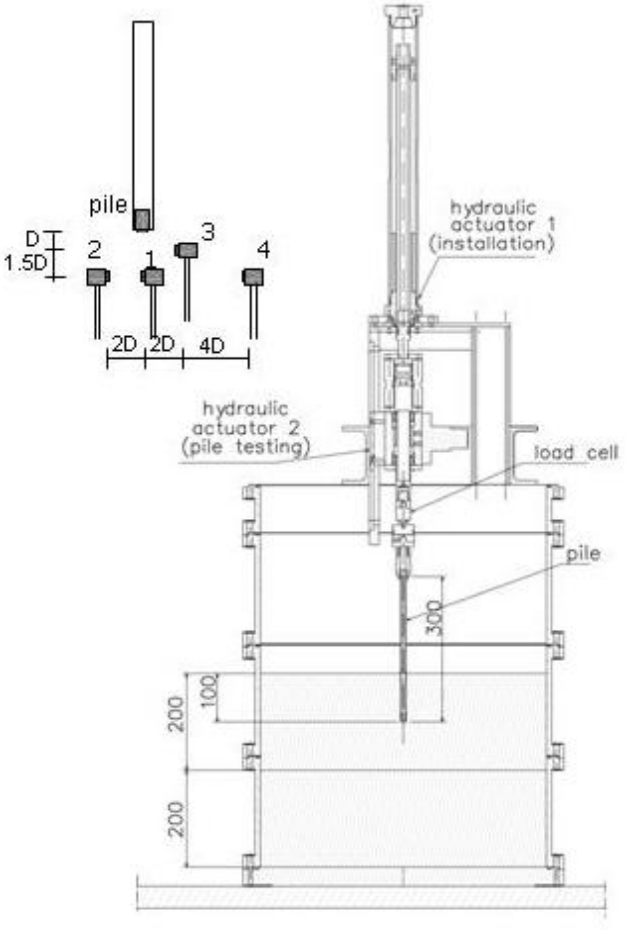

Figure 1. Test set-up (detail gives position transducers)

After preparation the sample at 1-g, it was placed in the centrifuge. On flight, the test program was carried out. The pile was jacked by the large actuator over 10D into the sand (initial depth of the pile toe was 10D). A static load Test (SLT was carried out up to pile displacement 10% of D. Afterwards three series of Rapid Load Tests (RLT) were carried out, with each series followed by a SLT. Each series of RLT was carried out with a constant duration of the load.

Table 1. Main properties of the samples

Parameters	Test 2	Test 3	Test 4
Relative density	54 %	36 %	65 %
Pore fluid	viscous	viscous	water
Viscosity	265 cp	292 cp	1 cp

Each series consist of four cycles with increasing displacement during the test 1%, 2% 5% and 10% of diameter. The loading durations of the series RLT were 48 ms, 18.5 ms and 9 ms.

During each test the following variables were measured: displacement of the pile, the force at the head and the toe of the pile, the pore fluid pressure at the pile toe and the pressure in the four buried transducers.

4 EFFECT OF THE PENETRATION RATE ON PILE RESISTANCE

This Chapter shows the differences between static and derived rapid force-displacement diagrams. These differences show the influence of loading rate of a RLT. All results are shown in the model scale. A complete overview of all results is given in Huy (2008). The following terms and variables will be used:

– Pile head force (F_{head}) is a directly measured parameter.
– Pile toe force (F_{toe}) is also a directly measured parameter.
– Shaft force (F_{shaft}) is derived from the difference between F_{head} and F_{toe}.

4.1 *Measured results*

Figure 2 shows the static load-displacement curves for both the pile head and the pile toe for all four SLTs in Test 3. The first SLT (SLT3-1) was carried out directly after pile jacking. The other SLTs were carried out after a series of four RLTs. The static load-displacement curves strongly depend on the initial density of the sand, as expected. The SLT results are shown on the first line ("small SLT") of each sub-table in Table 2.

Figure 3 shows the pile toe force-displacement curves measured during the static- and rapid load tests with a displacement 0.1D performed in Test 3. The influence of the penetration rate is clearly visible.

4.2 *Results at maximum displacement*

Figure 4 shows the dependency of the maximum pile toe force on the penetration rate of the model pile. The results are taken from all RLTs performed in Tests 2, 3, and 4 with an imposed displacement of 0.1D. The maximum toe force of the RLT (R_{max}) is normalised with the value of the SLT at the same magnitude of displacement (R_{sta}), carried out directly after the RLT. The static force at an imposed displacement of 0.1D strongly depends on the initial density of the sand. Due to the normalisation, the effect of initial density of the sand is removed from the results; the study focuses on the applicability of a RLT to measure a static maximum force

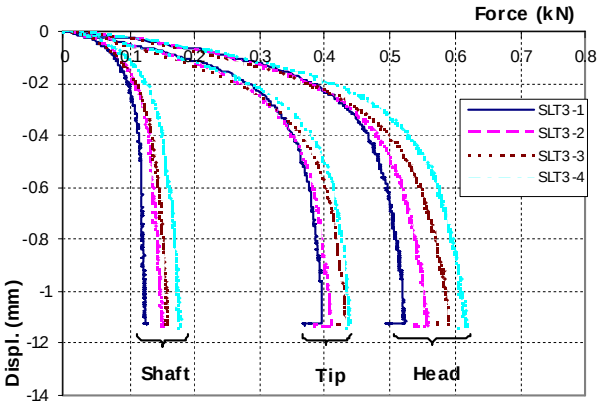

Figure 2 Static force-displacement curves in Test 3

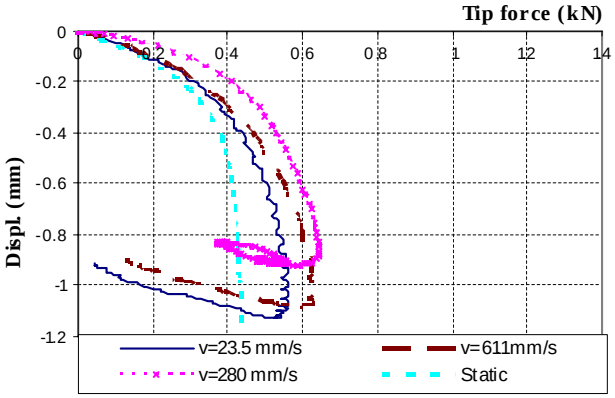

Figure 3. Toe force-displacement curves for RLTs in Test 3

The figure shows that the penetration rate causes an increase in maximum toe force of approximately 10% in Test 4, whereas the increment varies from 20% to more than 40% in Tests 2 and 3, depending on the rate. The increase of some 10% in Test 4 is interpreted as the load rate effect (viscous damping), and the additional increase in Test 2 and Test 3 is interpreted as the influence of the pore fluid viscosity. Comparison of the curves for Test 2 and Test 3 shows that the effect of initial density of the sand on these normalised curves is very small.

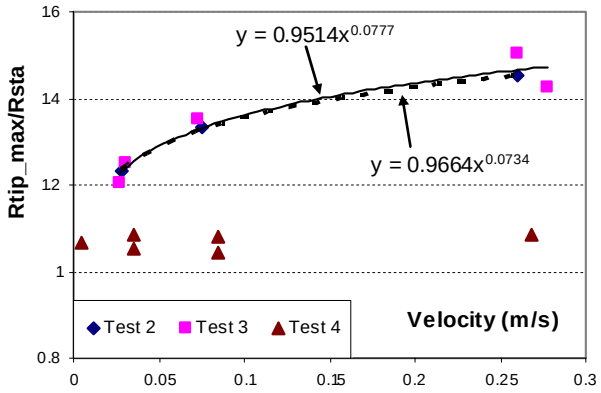

Figure 4. Effect of penetration rate on maximum toe force

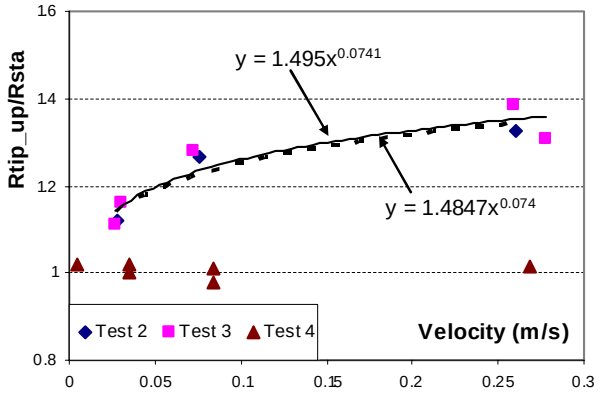

Figure 5. Effect of penetration rate on toe force at unloading point

Figure 5 shows the toe force (R_{up}) at the unloading point (where the pile reaches the maximum displacement), normalised with the maximum static value, as a function of the penetration rate. In engineering practice, the force at the unloading point is taken as equivalent static capacity. It is normally calculated using the force on the pile head minus the inertia force. The force at the pile toe is directly measured in this research, and correction for the inertia is therefore not required. Figure 5 shows that the penetration rate in the fully drained Test 4 does not affect the unloading point force. In the tests 2 and 3 however, the toe force in the unloading point is between 15% and 35% higher. The viscosity affects both values (R_{max}/R_{sta} and R_{up}/R_{sta}). The effect increases with increasing velocity. The trend lines for results from Tests 2 and 3 are also plotted in Figure 5. These are nearly identical, confirming again that the initial density appears to play no role.

4.3 *Results for smaller displacements*

Table 2 shows the observed force at the pile toe for the speeds and displacements applied. For low displacements, the influence of the loading speed is small. For higher displacement, the force at the pile tip in Test 2 and Test 3 increases in the tests with viscous fluid.

These test results are in agreement with the observations in the field that the initial stiffness of the soil around the pile toe is not influenced by the speed.

Table 2. Toe force [in kN] several speeds and displacements

speed	maximum force			
[mm/s]	1%D	2%D	5%D	10%D
small (SLT)	0.25	0.42	0.62	0.66
5-6	0.24	0.42	N/A	N/A
11-12	0.26	0.42	0.68	N/A
23-30	N/A	0.42	0.70	0.80
61-63	N/A	N/A	0.75	0.90

Test 2 medium dense sample, viscous fluid

speed	maximum force			
[mm/s]	1%D	2%D	5%D	10%D
small (SLT)	0.19	0.28	0.38	0.42
5-6	N/S	0.28	N/A	N/A
11-12	0.18	0.25	0.40	N/A
23-30	N/A	0.30	0.44	0.50
61-63	N/A	N/A	0.46	N/S

Test 3 loose sample, viscous fluid

speed	maximum force			
[mm/s]	1%D	2%D	5%D	10%D
small (SLT)	0.35	0.64	1.05	1.15
5-6	N/S	0.63	N/A	N/A
11-12	0.34	0.52	1.04	N/A
23-30	N/A	0.61	1.03	0.96
61-63	N/A	N/A	1.06	1.16

Test 4 dense sample, water

Legend: N/A means RLT is not carried out
N/S means RLT not succeeded

5 PORE PRESSURE DISTRIBUTION

5.1 *Pore pressure against the pile toe*

To understand the measured increase of the pile capacity due to the viscosity of the pore fluid, it is useful to focus on the pore pressure measurements in the soil around the pile toe during an RLT.

Figure 6 shows the pore pressure measured against the pile toe. The results of two RLTs with similar loading rate are shown: the maximum displacement is different (5% D and 10% D). The test with 10%D takes twice the duration of the test with 5% D.

The pore pressure first increases due to compression of the soil; then far before the end of

the test, a sharp decrease is observed. The moment is independent of the final displacement, so it is reasonable to assume that the sudden change is related to failure of the sand around the pile toe: failure leads to dilatancy and thus a decrease of pore pressure. Finally, when the RLT is finished, the generation of pore pressure stops and consolidation is observed. Figure 7 shows the pore fluid pressure at the sudden change for the RLTs of Test 2 with a lower speed. It can be concluded that the maximum pore pressure increases with decreasing loading duration (i.e. increasing loading speed). This clearly suggests that the dissipation of pore fluid plays an important role.

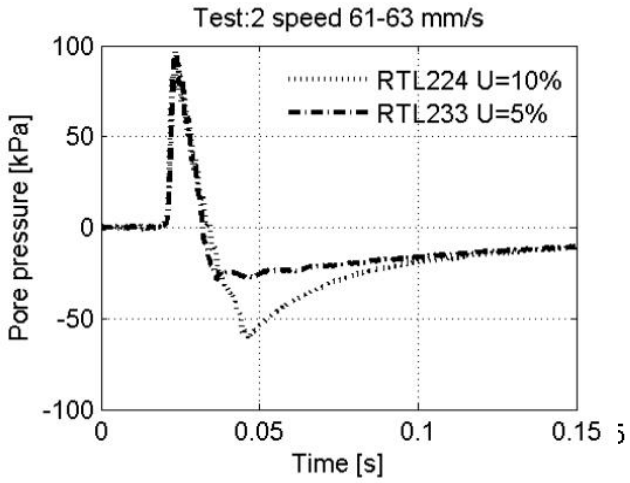

Figure 6. Pore pressure directly under pile toe during RLT Test 2

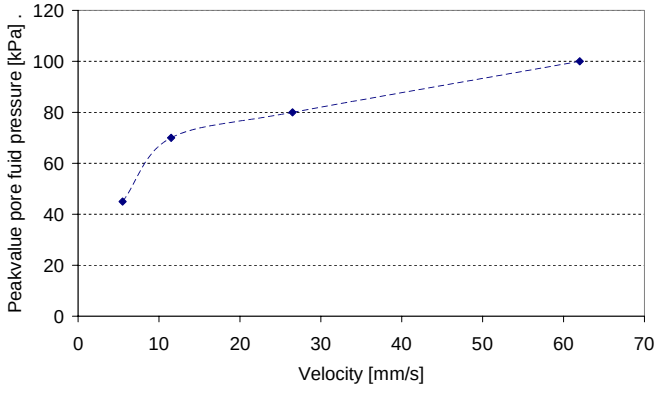

Figure 7. Peak value of pore fluid pressure against pile toe

5.2 *Pore pressure in the soil*

The pore pressure in the sand is the result of the excess pressure generated by failure and the dissipation by fluid flow. In this section, the results of two pore pressure transducers are shown: PPT-2 that is 2D from the pile axis and 2.5D under the pile toe and PPT-3, which is 2D from the pile axis and 1D under the pile toe (depth at the beginning of the test series).

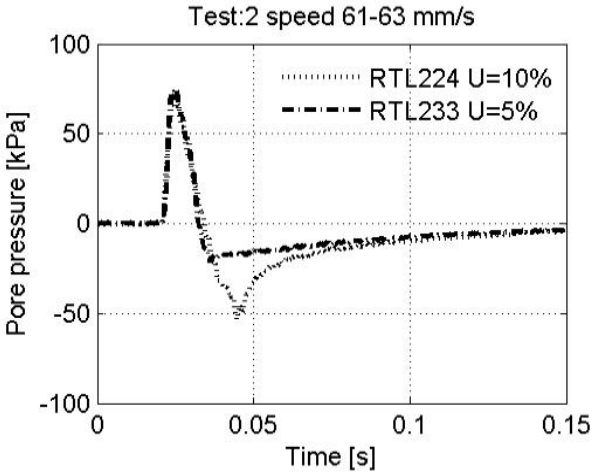

Figure 8. Pore pressure during RLT in PPT-2

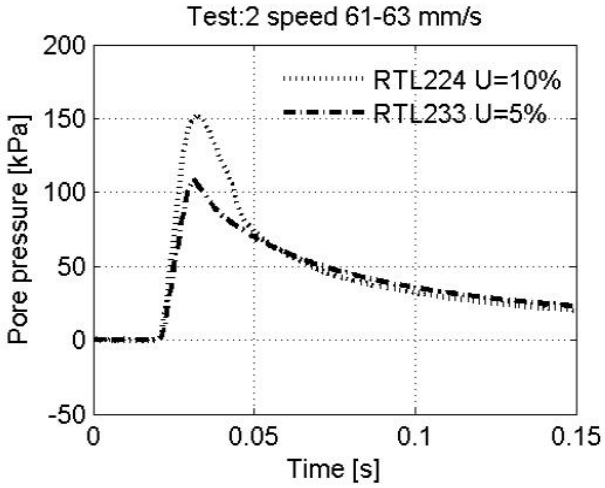

Figure 9. Pore pressure during RLT in PPT-3

Figure 8 shows results that are almost similar with the results directly under the pile toe (shown in Figure 6). Obviously, at that position the soil behaviour is comparable with the soil under the pile toe. This pore pressure transducer is close to the failure area. The value is smaller than at the pile toe. This might be explained from a higher generation or higher dissipation of pore pressure.

Figure 9 shows a different behaviour. The change from increasing to decreasing pore pressure is observed as well, but less pronounced and, for the higher loading rate, at a higher pore pressure. This suggests that the pore pressure response at this location is not directly induced by the soil behaviour at the position of the transducer, but by the migration of the negative pore pressures generated in

failure zone around the pile tip. At the slower test, the pore fluid has more time to flow leading to a lower excess of pore pressure at the moment of failure. At the end of the loading, the generation of pore pressure stops. At that moment, only smoothing of pore pressures due to migration of the fluid is active. This is seen by a small kink in the curves.

6 PRACTICAL CONSEQUENCES

Figure 10 shows the normalised toe resistance as a function of the dynamic drainage factor, as defined in Section 2. The "solid square" markers represents the ratio maximum force over the maximum static force (R_{max}/R_{sta}) at the same displacement; the "open circle" markers represents the ratio force at the unloading point over the maximum static force (R_{up}/R_{sta}) at the same displacement. Huy et al (2007) showed by calculations that the drainage factor is indeed a valid dimensionless indicator of dissipation of the excess pore water pressure. The centrifuge tests comprise both generation and dissipation of the pore water pressures.

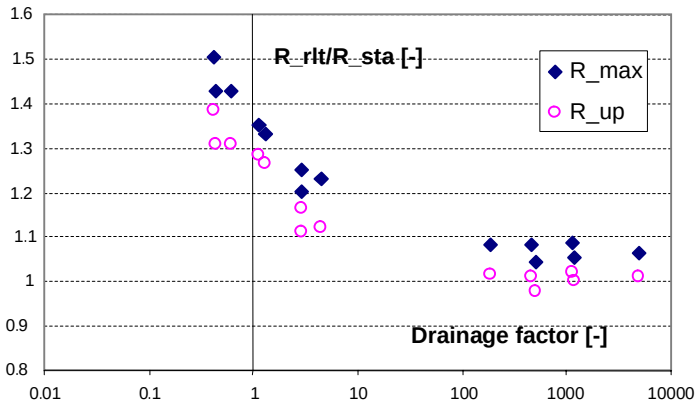

Figure 10. Normalized maximum pile toe force against drainage factor

From Figure 10, it can be estimated that a drainage factor of approximately 10-20 can be used to separate drained conditions (negligible effect of excess pore pressure) and the partially drained side (where the effect of excess pore pressure must be considered) for the in-situ rapid load test. The number of test results with a drainage factor between 4 and 100 is unfortunately limited, which hinders further specification of this value.

The range of the drainage factor for piles in sand is in practice between 0.5 and 1000, based on the following parameters: shear modulus G = 80 - 160 MPa, coefficient of permeability k = 10^{-5} – 10^{-2} m/s, loading duration T = 80 - 160 ms, and pile radius R = 0.15 - 0.4 m. For piles with a large diameter or piles in sands with a relative low permeability, the result of an RLT will be influenced by the effects described in this test.

The results of these tests explain the empirical results of McVay et al (2003) extended by Hölscher van Tol (2009). Assuming that the practical cases have a dynamic drainage factor of approximately 10, the estimated correction factor is 10%. This is in close agreement with the empirical result.

Significant errors will occur if the conventional unloading point method is used without considering this aspect. A correction for the excess pore pressure effect must be applied for an accurate prediction of the static bearing capacity of a pile from an RLT.

7 CONCLUSIONS

The results of the three centrifuge pile load test series have been presented. The model results are comparable with the results of a prototype rapid load test. The results may therefore be applied to the prototype scale. The tests were carried out on soil displacement piles in sand.

The following conclusions can be drawn from the test results:

- During a rapid load test on a displacement pile in sand, excess pore pressure is generated due to compression and shearing in the soil around the pile base.
- The toe resistance of the pile is higher during a rapid load test than during a static load test.
- If the dynamic drainage factor is larger than 10-20 (coarse sand) in a rapid load test, the maximum resistance at the pile toe is not influenced by the generation of pore water pressures. If the dynamic drainage factor is smaller than 10 (medium and fine sand), the excess pore pressure increases both maximum resistance and resistance at the unloading point. The application of a rate dependant factor for finding the static capacity from a rapid test is recommended.

These centrifuge tests offer good possibility to validate advanced calculation models for behaviour of the soil around the pile toe.

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