Centrifuge modeling of rapid load tests with open-ended piles

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ABSTRACT: Rapid and static load tests were conducted on open-ended and close-ended piles in the Deltares GeoCentrifuge. In flight, a pile was driven into the soil. Both fine-grained sand and silt beds were tested. Both the rapid and static soil resistances of a close-ended pile were higher than the soil resistance of an open-end pile in both sand and silt. For the rapid load test, the higher the penetration rate, the higher the maximum soil resistance. The ratio of maximum soil resistance between a rapid load test and static load test does not depend on pile type but on soil type: less than 1.0 for sand and higher than 1.0 for silt. The results show that centrifuge modeling can be applied for open-ended piles but then silt must be used as the soil material.

1 INTRODUCTION

Pile load tests are a standard procedure for the verification of pile load-displacement behavior as well as for prediction of the static bearing capacity of the pile. The methods used are the static load test (SLT), the dynamic load test (DLT) and the rapid load test (RLT). The tests vary in terms of the dimensionless wavelength $N_w = (T_f \times c_p)/L$ in which T_f is the loading duration, c_p is the pile wave velocity and L is the pile length. $N_w < 10$ for the DLT, $10 < N_w < 1000$ for RLT and $N_w > 1000$ for the SLT (Hölscher and van Tol, 2008). Although the SLT is the most reliable method, it is often too expensive and time consuming to apply routinely. The RLT is increasingly used because it is better in terms of execution, elaboration and quality assurance than the DLT (Middendorp et al. 1992) and is more suitable for use in offshore foundation engineering than the SLT.

Open-ended piles generally behave as though fully plugged during static loading but they can behave in a partially plugged way during rapid or dynamic loading, especially when loading rates are high (Bruno and Randolph 1999). The degree of plugging depends on several factors such as pile depth, pile diameter, loading rate and soil type... Different degrees of plugging are expected to result in different levels of soil resistance. An understanding of plugging during an RLT is important for the application of RLTs to open-end piles: if a pile plugs during an SLT but does not plug during an RLT, the RLT will be unreliable and may underestimate pile capacity.

Scale modeling of pile load tests offers a good opportunity to investigate this area. It avoids the high costs of field testing and offers additional possibilities compared with field testing. Centrifuge modeling is considered to be a reliable method due to the accurate representation of the stress state, especially the self-weight stress gradient, around and inside the model pile at a reduced scale. An experimental study of RLTs and SLTs with open-ended piles was performed with different soil types to examine plugging behavior in silt and sand, especially during RLTs, and to compare soil resistance in rapid and static conditions. Results from open-ended piles test are also compared with those from close-ended piles tests. This paper presents the results from four test series comprising several RLTs and SLTs.

2 DESCRIPTION OF RESEARCH

2.1 Centrifuge modeling

Given the requirement of stress similarity between the model (with the centrifuge length L_{model} and the centrifuge acceleration of a_{model}) and the prototype (with the length $L_{prototype}$ and the earth's gravity $a_{prototype}$), the scale factor is defined by means of Equation (1).

$$N = \frac{L_{\text{prototype}}}{L_{\text{model}}} = \frac{a_{\text{model}}}{a_{\text{prototype}}} = \frac{a_{\text{model}}}{g} \tag{1}$$

Table 1 shows the scale factors of some parameters on the basis of dimensional analysis, summarized by Taylor (2005). It should be noted that, by using centrifuge modeling, the dynamic event and the consolidation event have two different time scale factor, N and N^2 respectively. This different will be discussed later.

The experimental study was carried out in the GeoCentrifuge at Deltares (The Netherlands). Figure 1 shows the facility which consists of sand fill container, loading system of two hydraulic actuators... More detail on the facility of the centrifuge tests setup can be found in Huy (2008).

Table 1. Scale factors in centrifuge test.

Parameters	Model	Prototype
Length/Displacement	1	N
Acceleration	N	1
Time (dynamics)	1	N
Time (consolidation)	1	N^2
Mass	1	N^3
Velocity	1	1
Force	1	N^2
Stress	1	1
Strain	1	1

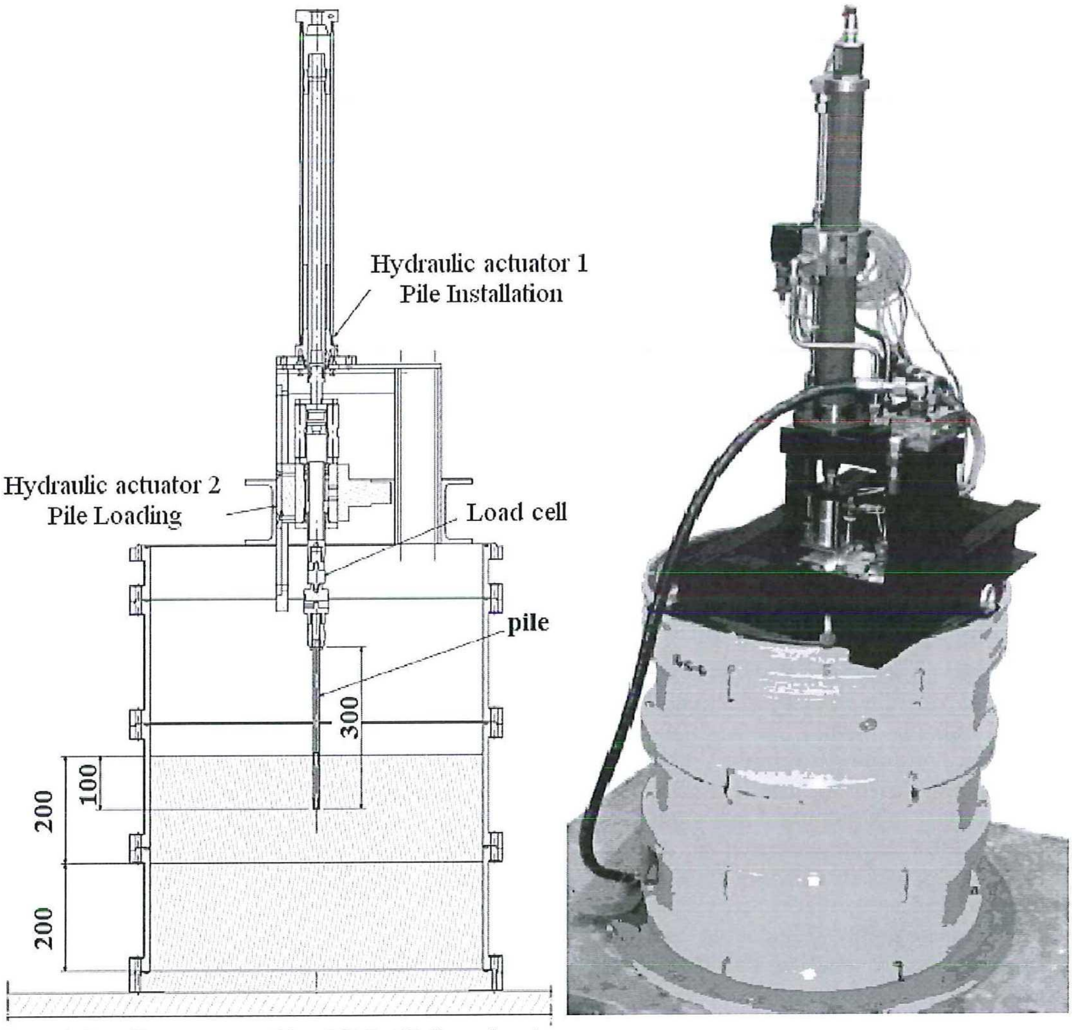


Figure 1. Centrifuge test setup (Huy, 2008). All dimensions in mm.

2.2 *Model piles*

The model pile was made from steel with a length of 300 mm, a diameter of 11.3 mm (D), wall thickness of 0.5 mm and mass of 875 gram for an open-ended pile and 1035 gram for a close-ended pile (M); this mass includes the pile mass and the mounting gear on the pile head. A load cell was mounted on the pile head to measure the applied force.

2.3 *Model materials*

Baskarp sand (d_{50} = 130 μm) and silt (d_{50} = 58 μm) were chosen for the tests. Table 2 lists the basic parameters for the soils (the quoted values for friction angle and permeability are at 65% relative density) and Figure 2 shows the grain size distribution curves.

To minimize the scale effects, the ratio of pile wall thickness to the mean grain size d_{50} needs to be larger than 10 and the ratio of the inner diameter of pipe pile to d_{50} must be larger than 200 (de Nicola and Randolph, 1997). The silt almost satisfies this condition (8.6 and 178). In the sand, the ratios are 3.9 and 79. In prototype terms, the test with silt corresponds to the normal use of open-end piles in sea-bed sand, while the test with sand is an extreme case in a fine gravel layer which is sometimes to be found in reality.

The soil sample was prepared by drizzling sand into water, followed by densification using impact loading (Rietdijk et al., 2010). This method made it possible to achieve a reasonably homogeneous and reproducible sample of 65% relative density (for these types of soils).

Table 2. Properties of soils.

Parameters	Units	Sand	Silt
Grain vol. mass	kg/m^3	2647	2650
d_{50}	μm	130	58
Min. porosity	%	34	42.2
Max. porosity	%	46.9	53.9
Internal friction angle*	degree	40°	38°
Permeability	m/s	12×10^{-5}	1.5×10^{-5}

*: determined by triaxial tests

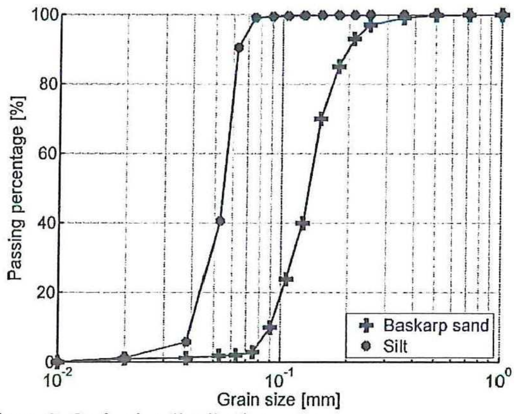


Figure 2. Grain size distribution curves.

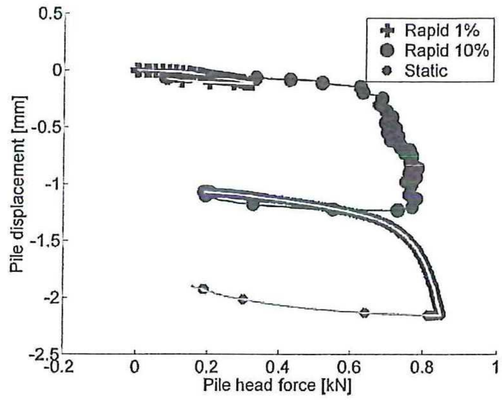
As mentioned on Section 2.1, the scale factors of dynamic event and consolidation are different (N and N^2) hence if the same soil type as in reality is used, the pore fluid must be N times more viscous to have a unification of the scale factors (Taylor, 2005). However in the authors' research group, it is still not feasible to saturate the silt bed with viscous fluid. Beside, the main idea of this research is investigation and comparison of the open-ended pile in sand and silt therefore water was selected as the model pore fluid for all tests. Based on the results of Huy (2008), the response of the pile under rapid loading will be drained, with water as the pore fluid in both cases (Baskarp sand and silt) then the effects of excess pore pressure can be ignored.

2.4 *Test programme*

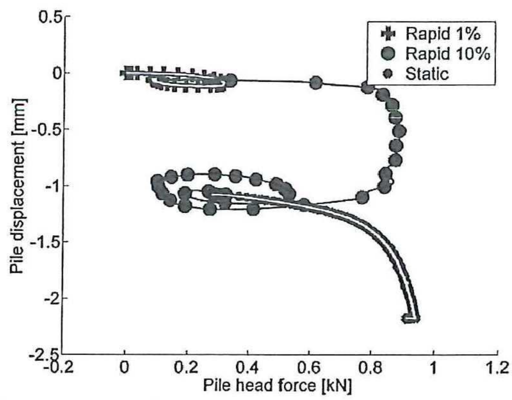
Three tests were performed at the gravity level N = 40 with the same loading programme: two tests in silt, one with an open-ended pile (OEP) and one with a close-ended pile (CEP); and one test with an OEP in sand. During the tests, the pile was first pushed from the pre-embedded depth of 10D to a depth of 20D using the large hydraulic actuator. Two RLTs with average velocity of 23.5 mm/s (Slow test) were then performed with displacements of 1% D (Rapid 1%) and 10% D (Rapid 10%) respectively (duration 10 ms) and two other RLTs with average velocity of 125.6 mm/s (Fast test) and, finally, an SLT with a displacement of 10% D (Static) was performed. The results from one test conducted previously (also at Deltares) with a CEP in sand (Huy et al., 2008) are also shown here for the purposes of comparison.

3 RESULTS OF THE CENTRIFUGE TEST

Figure 3 shows two typical results for measured pile head force and applied pile displacement. The pile head forces have been corrected for the self-weight of the pile.



(a) Average velocity of 23.50 mm/s



(b) Average velocity of 125.60 mm/s

Figure 3. Measured load-displacement curves.

The applied force can be considered rapid, even though, compared with a field test (*e.g.* Matsumoto and Nishimura, 1996), the generated force has very high gradients at the beginning and at the end of loading and a long duration of maximum force, especially in the Fast test. The influence of this force generation will be discussed further on Section 4.

On Figure 3(b), there are loops at the end of loading in the Rapid 10% of Fast test. This is the overshoot of the loading actuator when it is controlled to achieve the fastest loading duration of 10 ms. As the overshoot is caused by the mechanics of loading system and happens after the considered loading duration of 10 ms, this overshoot was not taken into account.

During an RLT, the pile can be seen as a rigid body. In that case, the force on the pile head ($F_{measured}$) is equal to the sum of the soil resistance (F_{soil}) and the inertia force ($F_{inertia}$) of the pile (Middendorp et al. 1992). The soil resistance can therefore be calculated from:

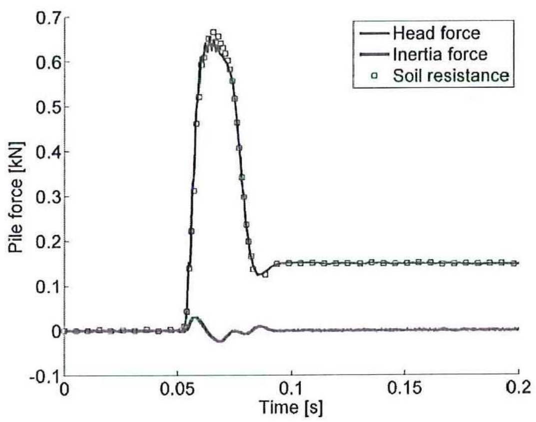
$$F_{soil} = F_{measured} - F_{inertia} = F_{measured} - M \times a \qquad (2)$$

where M is the pile mass and a is the pile acceleration. The acceleration is calculated numerically as the second derivative of the measured pile displacement at all time steps.

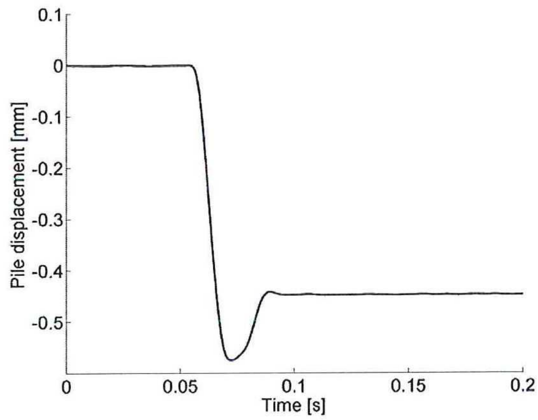
$$u = [u_1, u_2, ..., u_i, ...u_n] \qquad (3)$$

$$a_i = \frac{u_{i-1} - 2u_i + u_{i+1}}{\Delta t^2} \qquad (4)$$

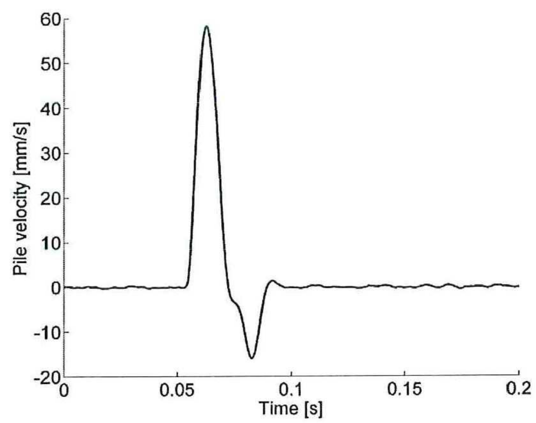
Figure 4 shows an example of the measured pile head force, inertia force and resulting soil resistance and prescribed pile displacement from the RLT with silt. This soil resistance still includes velocity effects due to rapid loading. In Figure 4, the velocity and acceleration of the pile are also presented.



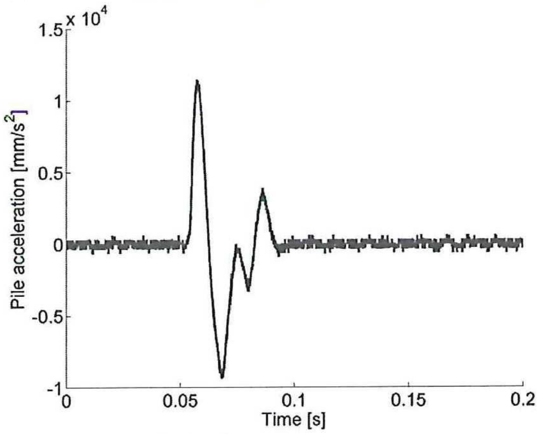
(a) Forces in time



(b) Pile displacement in time



(c) Pile velocity in time



(d) Pile acceleration in time

Figure 4. Example of measured and calculated signals.

4 DESCRIPTIONS AND DISCUSSION OF THE MODEL PILE TEST RESULTS

This section describes the comparison of SLTs and RLTs in silt and sand in detail. It should be noted that, from this point on, the soil resistance force during the RLT will be the calculated pile head force after eliminating the inertia force of the pile, and that all the numbers and quantities are in terms of model scale (N = 40 g).

4.1 Pile installation

As described above, the model piles were pushed into the soil medium with the large hydraulic actuator from the initial depth of 10*D* to the final depth of 20*D* (from distance of 250 mm to distance of 140 mm from the container base) with a driving velocity of 10 mm/min. At this very low driving speed, the installation process can be considered as static jacking and the pore pressure does not build up.

Figure 5 shows the pushing records from the installation phase of open-ended pile in sand and silt beds. It is clear that the installation of the model pile in sand requires about 30% more force than in silt. A possible explanation is the grain size of sand, which is 2.5 times larger than the grain size of silt and quite large compared to the thickness of the pile wall.

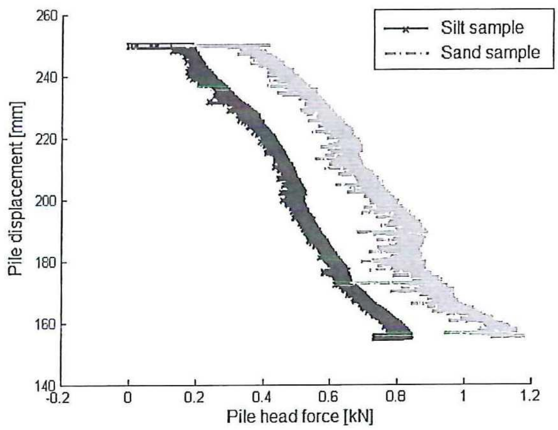


Figure 5. Load-Displacement curve for installation phase of open-ended pile.

4.2 Soil resistance and penetration rate effect

Figures 6 and 7 show the soil resistance-displacement curves for different maximum displacement values. Since the duration of the loading was the same in all tests, the loading speed and then the penetration rate also varies between these tests. Figure 6 shows the results of the tests in silt and Figure 7 shows the results of the tests in sand. Part a) shows the results for the OEP and part b) shows the results for the CEP. The test for the CEP in sand can be found in Huy et al. (2008). The average velocities in all of these tests are 23.50 mm/s. Table 3 presents soil resistance values of two rapid loadings at 10% *D* displacement and corresponding static loadings in all four tests.

Generally, the soil resistance-displacement curves of RLTs have quite similar patterns: the force first rises quickly to its maximum value, then stays high at about the maximum value before finally falling rapidly. This steep loading pattern deviates from the loading pattern observed in field tests with a shallower increase to the maximum load and a shallower decrease to zero. This is a limitation of the hydraulic loading system, as seen in Figure 4.

There is almost no improvement in the SLT values of static loadings in each tests although between them there is several rapid loading.

The soil resistance observed during the SLTs in sand was higher than in silt: soil resistance with the OEP was 1.5 times higher; a factor 2 was found for the CEP. These differences could possibly be explained by the properties of the soil materials. Firstly, the friction angle of Baskarp sand is 1-2° higher than the friction angle of silt (at a relative density of 65%). Based on Brinch-Hansen (1970), the difference between 38 and 40 degree leads to a 30% higher bearing capacity of a strip foundation, this is another observation but it can give some suggestion. Secondly, the d_{50} of the sand is 2.5 times larger than the d_{50} of the silt. The d_{50} governs the thickness of the shear band along the pile shaft, at the outer surface for the CEP pile and at the outer and inner surface for the OEP pile (Wolf et al., 2003; Wood, 2002), and at the pile tip which is normally about 8-12 d_{50}. It is well known that in the shear band, soil is loosen and the shear stress reduces hence the shaft resistance reduces also. This explains why the static resistance of CEP pile in sand is factor 2 higher than that in silt but this factor is only 1.5 for OEP pile.

The maximum soil resistance of the close-ended pile is higher than the maximum soil resistance of the open-ended pile in both the RLT and SLT: about 30% for the sand sample and 10% for the silt sample. For the RLT, the higher the penetration rate, the higher the maximum soil resistance, about 10% difference between the slow test and the fast test in silt test and 5% difference in sand test. This holds for both close-ended and open-ended piles.

To compare the soil resistance during static and rapid loading, two factor R_M and R_{UP} are defined as:

$$R_M = \frac{F_{\text{Max load}}}{F_{\text{Static}}} \tag{5}$$

$$R_M = \frac{F_{\text{Max load}}}{F_{\text{Static}}} \tag{6}$$

in which $F_{Max\ load}$ is the maximum soil resistance during rapid load test, $F_{UP\ load}$ is the soil resistance at the unloading point of rapid load test, F_{Static} is the maximum soil resistance at the static load test. It should be noted that $F_{Max\ load}$, F_{Static} are calculated at the same displacement.

With the sand sample, the maximum soil resistance during the RLT, of both CEP and OEP, is comparable with the maximum soil resistance during the SLT: $R_M \sim 0.95$ (5% lower) for the slow tests and $R_M \sim 1$ for the fast test. With the silt sample, $R_M \sim 1.07$ (7% higher) for slow test and $R_M \sim 1.19$ (20% higher) for fast test, these differences apply to both the close-ended and open-ended piles.

4.3 Unloading-point method

The ratios of soil resistance at the unloading point during the RLTs to maximum soil resistance during the SLTs were quite different in all tests. With slow tests, except the CEP in sand has $R_{UP} = 0.78$, three other tests has $R_{UP} \sim 1$ as expected from the definition of unloading-point method (Middendorp et al. 1992). With fast test, R_{UP} is significantly less than 1. This strange phenomenon can be explained from Figure 3, either of the steep loading pattern or of the high inertia force, especially the parts of after maximum load.

Because of very high acceleration, fast test reaches maximum prescribed displacement at only 20% maximum load; while slow test reaches maximum prescribed displacement at 92-98% maximum load. As pointed out by McVay et al. (2003) and Paikowsky (2006), in order to have good prediction of pile bearing capacity by UP method, the assumption of "soil resistance at the UP coincides with static capacity of the pile" is considered as significant. From this point of view, with the hydraulic loading system used in this research, the UP method is only applicable with slow rate test only.

4.4 Plugging

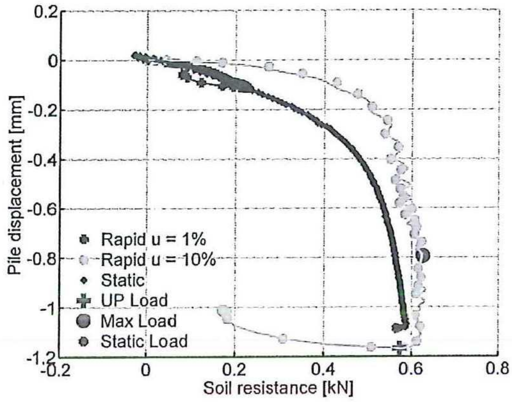
After installation and all loading phases, the pile was dug out. The final plugging length of the soil inside the model piles was 55 mm (5*D*) with silt and 22 mm (2*D*) with sand. The total displacement of each pile was 122 mm (10.8*D*), with the total embedded length of each pile being 241 mm (20.8*D*). Plugging length as a percentage of the total embedded length of pile was about 23% for silt and 9% for sand. These are relatively extreme values for plugging length when compared to those generally observed in reality (10-20% of the embedded length of the pile) (Randolph et al., 1991).

A close inspection of Figure 6 shows that the SLTs for the OEP and the CEP are almost identical. The RLTs for all piles show that the force declines after reaching the maximum. With the OEP, the force decreases slightly more than for the CEP and is slightly more perturbed. The soil column inside the pile in sand tests may have slipped during the RLTs as the increasing bearing capacity exceeds the plug capacity, Figure 7(a); this does not happen in silt tests, Figure 6(a). However, the differences are small and the soil resistance of the open-end pile was quite comparable to the soil resistance of the close-ended pile. This suggests that the piles plug during both SLTs and RLTs. The motion of the plug would have to be measured directly to obtain more accurate information.

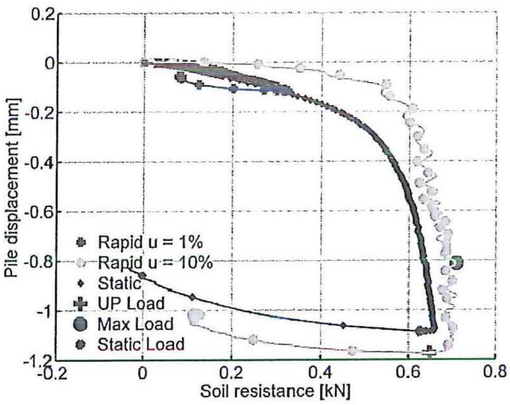
Since the measured plugging length as well as the plug behavior during SLTs and RLTs of OEP is highly dependent on the material, it is important to use a correctly scaled material to avoid potential influence from scaling effect, especially in respect of the interaction between the pile annulus and the soil (de Nicola and Randolph, 1997). In this research with $N = 40$, silt must better be used than sand.

Table 3. Soil resistance in RLT and SLT at displacement of 10% D.

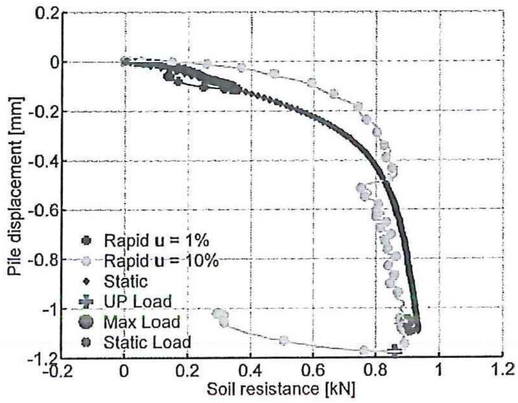
Rapid load test of 10% *D* displacement		Max. velocity [mm/s]	Average velocity [mm/s]	Rapid loading Max load [kN]	Rapid loading UP load [kN]	Static load [kN]	R_M	R_{UP}
Close-ended Sand	1	57	23.50	1.27	1.05	1.35	0.94	0.78
	2	335	125.60	1.33	1.22	1.35	0.99	0.90
Close-ended Silt	1	54	23.50	0.71	0.65	0.66	1.07	0.98
	2	124	125.60	0.79	0.24	0.66	1.19	0.37
Open-ended Sand	1	51	23.50	0.90	0.86	0.93	0.96	0.92
	2	121	125.60	0.95	0.43	0.96	1.00	0.45
Open-ended Silt	1	53	23.50	0.63	0.57	0.59	1.06	0.98
	2	116	125.60	0.70	0.30	0.61	1.15	0.50



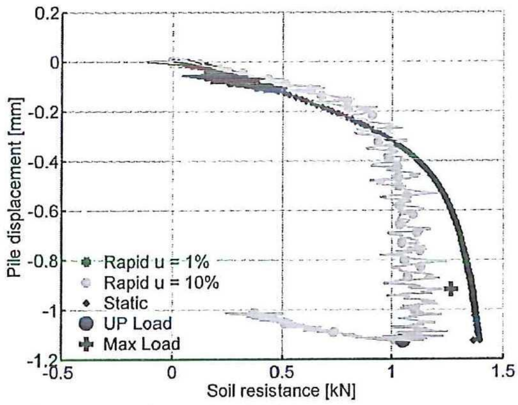
(a) Open-ended



(b) Close-ended
Figure 6. Load-Displacement curve for pile in silt.



(a) Open-ended



(b) Close-ended (from Huy, 2008)
Figure 7. Load-Displacement curve for pile in sand.

5 CONCLUSIONS

This paper described experimental work investigating soil plugs in open-ended piles in a geotechnical centrifuge. Both static and rapid load tests were studied in two types of soil: fine-grained sand and silt.

The conclusions can be summarized as follows:

1 Centrifuge testing is a feasible and efficient approach to studying the behavior of open-end piles.
2 The soil resistance in tests with sand was higher than in tests with silt and was higher for close-ended pile than for open-ended pile. This holds for both rapid load tests and static load tests. Within rapid load tests of the same soil type, the higher the penetration rate the higher the maximum soil resistance.
3 The unloading point method did not work well with loading tests which have steep increase of loading force or high inertia forces.
4 The proper scaling of an open-end pile requires proper scaling of the grain size. Silt must be used for a 1:40 scale.

The research is still ongoing. To improve out understanding of plugging behavior and the impact of plugging on open-end pile capacity during RLTs, the preliminary tests can be improved by:

1 Increasing the number of test to investigate the repeatability.
2 Measuring the plugging length during installation and all successive static and rapid loading steps;
3 Examining the influence of other factors as generated excess pore pressure, drainage condition and initial soil density.

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