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Centrifuge Modelling of Suction Pile Installation Using a Percussion Technique

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ABSTRACT

Small scale tests have been carried out in the University of Delft geotechnical centrifuge in order to examine the behaviour of suction piles during installation by the percussion method. In this technique, the driving force used to penetrate the pile into the sea floor is not obtained by continuous pumping, but by creating short pressure pulses. This method was thought to reduce upheave and to allow installation of piles under conditions in which the conventional method fails.

The effects of several parameters were investigated, including pulse duration, pile diameter, soil type and flatness of the sea floor. The tests indicated that the percussion method in particular shows advantages in cases where the conventional installation technique is less successful or fails.

KEY WORDS: suction pile installation, geotechnical centrifuge, percussion technique, suction emplaced pile.

INTRODUCTION

In recent years, suction piles have been applied increasingly often in offshore engineering (Senpere et al., 1982). Suction piles are attractive because of the convenient method of installation. Furthermore, the piles can be subjected to a large variety of loading conditions. In cases where they are used as an anchoring system for floating structures, the piles are mainly subjected to horizontal loading. In several cases the piles are subjected to vertical tensile or push loading. The loading conditions may exhibit a cyclic behaviour as a result of wave action.

In sandy soils a pile with a diameter of 9m and a height of 10m can be installed in 1-3 hours, using only a suction pump. The installation also proceeds easily in clay. However, there are a number of circumstances in which the installation does not always proceed well. Examples are the use of suction piles in coarse material and in layered soils. Furthermore, there is a preference to use more slender piles. However, slender piles generally result in more upheave and penetration refusal through plugging.

Despite the wide use of suction piles, details of the influence of several parameters have remained unknown. In order to increase the level of understanding, the installation process in sand was investigated by means of centrifuge tests (Allersma et al., 1997). There were found to be linear relationships between pressure and such parameters as height, diameter and wall thickness. Subsequent test programs (e.g. Allersma et al., 1998; El-Gharbawy et al., 1998; Narasimba et al., 1997) focused on the static and cyclic, horizontal and vertical bearing capacity of suction piles in sand and clay.

The test programme described in this paper was related to a new suction pile installation method. To increase the range of applications, a method has been developed where the pile is installed by a percussion technique. Instead of continuous pumping, the installation is performed by short pressure shots. The prevailing belief was that the method has advantages in cases where the continuous pumping method fails.

The relative ease with which parameters can be changed means that small scale tests are preferable for examining the new installation process. The soil type can be varied, as can the dimensions of the suction pile and other process conditions. In a small scale test, however, problems arise concerning the stress-dependent behaviour of soil. Furthermore, the measured loads and pressures are so low that measurements are not sufficiently accurate to visualize differences in design. These restrictions can be overcome by performing the tests in a geotechnical centrifuge. In a centrifuge the soil stresses over a similar depth are the same as in the prototype situation. At 50 times earth's gravity, a suction pile with a height of e.g. 3.5 m and a diameter of 3 m can be simulated with a pile 70 mm high with a diameter of 60 mm. It should be noted that the scale factor also applies to the particle size and effective stress.

The pressure, displacement and water volume can be measured in the course of the tests, so that differences in installation methods can be visualized.

PRINCIPLE OF THE SUCTION PILE

A suction pile is a large-diameter steel cylinder that is closed at the top either by a dome-shaped section or by a flat stiffened plate. The pile is open at the bottom. Pump inlets and relief valves are installed at the top, along with the attachment lug for the pile chain.

The pile, which can be launched from an installation vessel or from the aft deck of a supply boat, must be landed softly on the sea floor. The cylinder is lowered to the sea floor with the valves open so that the enclosed air can escape rapidly.

Once the pile has penetrated the sea floor by its own weight, the relief valves are closed. Additional weights, which ensure sufficient penetration of the skirt into the soil, are usually needed in cohesionless soils such as sands to avoid piping when the pumps are started.

Removing the trapped water from the pile by means of pumps mounted on the top causes a difference between the external hydrostatic water pressure and the water pressure inside the pile. The pressure difference generates the driving force for soil penetration. After a certain amount of penetration, however, the resistance can become so large that the pressure difference is not great enough to continue the installation. In permeable soils, groundwater will flow through the pores to the tip of the pile during pumping, so that local fluidization reduces the soil stress around the tip and between the pile wall and soil plug. The effect of this reduction is that the driving force is sufficient to ensure penetration of the pile. Pumping is stopped after reaching the designed penetration depth. In general this depth is reached in about 1-3 hours, depending on the soil configuration, the pile dimensions and the pump capacity.

After installation, pore pressures in the soil regain their initial values. The loads are therefore resisted by the soil in a similar way to a conventional driven or drilled pile with regard to friction. The pump, the air valves and any measuring equipment mounted on the top of the pile can be made retrievable for recovery after complete installation.

INSTALLATION BY PERCUSSION

In the case of installation of the suction pile by percussion, the pumping system is enhanced with the addition of a depression vessel (Fig.1). The vessel is placed under vacuum by pumping out water from the inside of the vessel prior to any action. A crossover valve is then operated, causing an abrupt pressure difference between the inside and outside of the pile, which causes a penetration of the pile over a certain length. When the balance in pressure between the depression vessel and the pile has restored, the valve is switched back, allowing a vacuum to be established in the depression vessel again. This process is repeated until the pile has fully penetrated into the soil. At that time the installation unit can be removed. Although a more complicated pumping package is required, the technique is believed to have the following significant advantages:

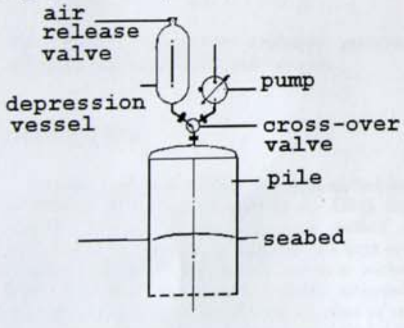

Fig.1 Diagram of the percussion system.

- the maximum pressure difference is directly available;
- no frequency control of the pumping system is necessary;
- pump cavitation is avoided;
- the penetration proceeds more effectively;
- the risk of penetration refusal is substantially reduced in coarse soils and in an uneven seabed;
- smaller pile diameters can be used.

TEST TECHNIQUE

A mathematical description of the installation process is very complicated, especially in the case of percussion. Furthermore, large scale tests to investigate the advantages of the percussion method would be very expensive and time consuming. In order to obtain an impression of the effect of the new installation method, a series of orientation tests were performed at 1g under small scale conditions in the first instance (Allersma et al., 2000). The small scale tests showed that the percussion method tends to dominante in cases of; installation in coarse sand, slender piles in fine sand, and installation in an uneven sea floor.

Fig.2 The University of Delft geotechnical centrifuge.

Visualization of the differences between the various methods was not always easy to achieve as a consequence of the low values of the measured parameters in the 1g tests. Furthermore, the fact that 1g tests are probably somewhat unrepresentative of the prototype conditions gave rise to a decision to perform a similar test program in the geotechnical centrifuge (Allersma, 1994) of the University of Delft (Fig.2). The centrifuge is a relatively small device with a diameter of 2.5 metres. Samples with a weight of 400N can be accelerated up to 150g. The small size of the centrifuge makes it very convenient to use, and allows a large number of tests to be performed in a short period. The tests can be controlled by a PC-compatible computer that is located on the rotating part of the centrifuge. This configuration allows noise-free measuring signals to be obtained, which guarantees accurate monitoring and control of the test set-up.

The tests discussed in this paper were performed at an acceleration of n=50g. The vertical effective stress σ_v' in the soil in the model with a unit weight γ at depth h can be described as follows:

$$\sigma_v'=n(\gamma-\gamma_{water})h_{model} \qquad 1)$$

A prototype suction pile with a diameter of D=3.25 m and a height of H=3.15 m can now be simulated using a scale model of D=65 mm and H=63 mm.

TEST SET-UP

A diagram of the test set-up is shown in Fig.3. A plastic or steel pile e.g. with a height of 63 mm and diameter of 65 mm is placed with the open end on the surface of a saturated sand bed. The top of the pile is closed. The container with the soil sample (height = 110 mm, diameter = 200 mm) is placed in a vessel (height = 360 mm, diameter = 280 mm), which can be pressurized to 500 kPa. The interior of the pile is connected to atmospheric pressure via a flexible tube and an electropneumatic valve. As a matter of interest, the commercially available valve was designed for air only, but a number of modifications were made to make the valve suitable for operating with water.

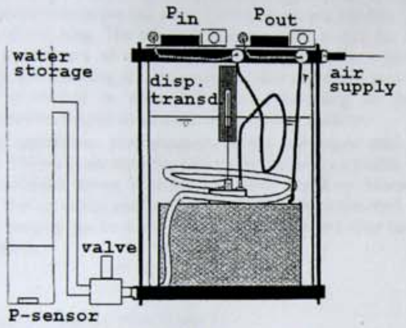

Fig.3 Test set-up to simulate suction pile installation.

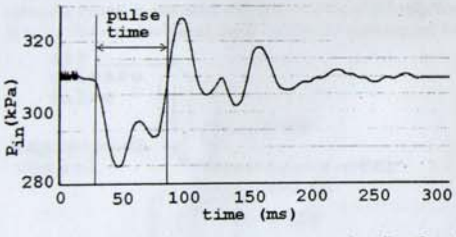

Fig.4 Typical graphical output of pressure in pile (P_{in}) during actuation of the valve.

When the vessel is pressurized, pumping action can be simulated by opening the valve. Since the pressure in the pile tends to atmospheric pressure, a pressure difference is created between the interior of the pile and the surrounding water. A specific water depth can be simulated by simply adjusting the pressure in the cell. The valve can be controlled by the on-board computer. It is possible to open the valve for long or short periods (the shortest opening time is approximately 50ms). A typical example of a pressure pulse is shown in Fig.4. There is a delay between application of the electrical signal and the reaction of the valve (Fig.5), requiring subsequent estimation of the actual opening time by reference to the graph of the pressure difference between the inside and outside of the pile plotted against time. It appeared that the pressure pulse is not a well defined square wave. Second order effects are responsible for the complicated wave shape that is visible. In the first instance a number of valleys can be observed, indicating that the pressure in the pile is lower than the outside pressure. The pressure then becomes higher, as a result of the speed acquired by the pile at the moment of closing the valve. After some oscillation the pressure becomes equal to the outside pressure. The pulse time is estimated from the graph as shown in Fig.4.

Several parameters were measured in order to monitor the progress of the test. In the first instance, the pressures inside (P_{in}) and outside (P_{out}) the pile were monitored by means of pressure transducers. The displacement of the pile was measured by an LVDT. The water flow during installation was deduced from a sensor which measures the hydrostatic pressure in the container which is connected to the output of the valve. The upheave was measured afterwards by a ruler.

MODEL PREPARATION

The sand samples were confined in a circular container with a diameter of 200 mm and a height of 110 mm. The sand sample was made as dense as possible. Dense samples were obtained by knocking and shaking the sample box. Three different sand types were used (D in mm):

Fine : $D_{90} = 0.14$: $D_{50} = 0.13$: $D_{10} = 0.11$: $k = 7.10^{-5}$ (cm/s)
Medium: $D_{90} = 0.34$: $D_{50} = 0.25$: $D_{10} = 0.19$: $k = .03$ (cm/s)
Coarse : $D_{90} = 0.52$: $D_{50} = 0.50$: $D_{10} = 0.37$: $k = .06$ (cm/s)

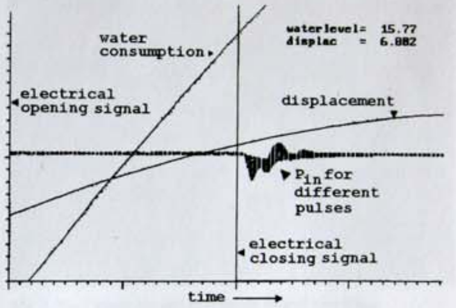

Fig.5 Real time output of a typical test simulating installation by percussion method.

The friction angle of the medium sand was ϕ=33°, and the unit weight γ=17 kN/m^3 (n = 33%). The values of the other sand types were close to those of the medium sand. The friction angle between the pile and the sand was determined by a shear box test and was found to be 22°.

After preparation of the saturated soil bed the confining container was placed in the vessel. The suction pile was then connected to the tubes and placed carefully on the surface of the soil layer. In order to avoid piping, a certain amount of initial forced penetration (ca 15% of the pile height) was applied in most tests. A guide system was used to prevent the pile from becoming unbalanced by the tubes. The vessel was filled with water, so that the top of the pile was covered by at least 20 mm of water. The vessel was then covered with a cap and placed on the platform of the centrifuge basket to allow connection of the test device to the on-board computer and the air system. After the required acceleration had been reached (50g in most tests), the vessel was pressurized by activating an electropneumatic valve. The pressure can be adjusted by changing parameters in the computer program. Performance of the test is then possible by activating a second electropneumatic valve from the computer keyboard. The simulation of either continuous pumping or the percussion technique is possible. During a test the principle parameters are visible in real time on the screen. A typical example of the screen output is shown in Fig. 5.

SUCTION PILES

Use is made of suction piles with a variety of dimensions. The piles used most often were made of transparent plastic (which allows observation of the sand surface inside the pile). A diagram of a typical pile is shown in Fig.6. The pile was equipped with a filter to prevent sand transport during installation.

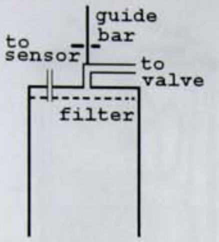

Fig.6 Diagram of suction pile.

Sand transport would influence the upheave observation, and sand could block the valve. A connection is available to monitor the pressure in the pile during installation. Since the tubes are relatively rigid at 1g a guide bar was used to keep the pile in place during preparation.

The effective height of the standard pile was H = 63 mm with an inner diameter D = 65 mm. The wall thickness was W = 1.3 mm. At 50g the dimensions have to be multiplied by 50 to obtain the prototype size. This means that the wall thickness is large in comparison with the prototype conditions. The reason for this is that it is not possible to make very thin plastic piles. Furthermore penetration is more critical at a larger wall thickness, so that it was better possible to visualize if the different installation methods were successful or not. An attempt was made in the tests to create situations in which one of the installation methods fail. A medium-sized pile with dimensions H = 92 mm; D = 50 mm; W = 1.3 mm and a slender pile with H = 82 mm; D = 30 mm; W = 1.5 mm were used.

In a previous investigation (Allersma et al., 1997) the behaviours of piles with different dimensions were compared in more detail. In this research programme attention was focussed on the behaviour of the pile in relation to different installation methods. For that reason no attempt was made to accurately standardize the dimensions of the different piles

BEHAVIOUR OF A STANDARD PILE IN MEDIUM SAND

The first series of tests were carried out in order to determine the limits of the installation pressure. If the pressure difference is large, installation proceeds under all circumstances. The pressure difference, dP, between pile P_{in}/P_{out} is not a parameter that can be controlled directly. The pressure difference is dependent on the pressure in the vessel, the resistance of the discharge tube and the permeability of the soil. The strategy was to make an adjustment to the pressure in the vessel and subsequently to examine how the pressure developed during the test. No penetration occurs if the pressure is too low. For medium sand a vessel pressure of 120 kPa was required to cause full penetration of the pile.

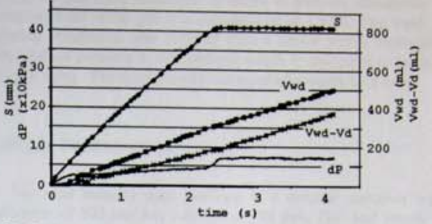

Fig.7 Measured parameters during penetration of a suction pile at 50g in medium sand during continuous pumping.

A diagram of the measured parameters is shown in Fig.7. An almost linear displacement, S, in time can be observed. The moment of full penetration is clearly visible. The pressure difference, dP, increases proportionally with the displacement up to dP = 50 kPa. A sudden jump in the pressure (dP) can be observed just after full penetration. The total water consumption, Vwd, appeared to have an almost linear relationship with the penetration. The water consumption excluding the volume of the pile, Vwd-Vd, is also shown. A kink can be observed after full penetration. It appeared that the volume of the additional water is about 2.5 times the volume of the pile.

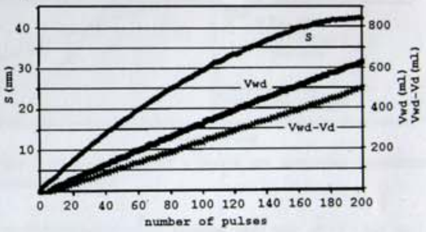

Fig.8 Measured parameters during penetration of a suction pile at 50g in medium sand during installation by percussion.

Fig.8 shows the test parameters during installation by the percussion method. The horizontal axis shows the number of pulses. The pulse duration was approximately 50 ms. The time between the pulses was ca 1s. In Fig.5 all the pulses are plotted. The valleys and so the pressure difference become larger when the pile reaches a greater depth. The value was close to the pressure difference occurring at a similar depth during continuous pumping. However, in the percussion test a larger pressure (150 kPa) in the vessel was required to achieve a pressure difference of dP = 60 kPa. It can be seen in Fig.8 that full penetration is less clearly defined than in the continuous pumping test. There appeared to be a linear relationship between water consumption and the number of pulses. The water consumption after installation in medium sand appeared to have almost twice the value observed in installation by continuous pumping. A tendency that could be observed was that the percussion technique results in a lower upheave (13%) than in the case of continuous pumping (17%). Furthermore it was observed that piping did not occur so soon in the beginning of the tests, in the case the percussion method was applied. Piping can be a serious problem when the sea floor is not flat.

INFLUENCE OF DIFFERENT PARAMETERS

In order to gain a better insight into the installation method by percussion, the influence of several parameters were investigated. The permeability of the soil was changed in order to determine the limits of the installation methods. It was found that in coarse sand (k=.06 cm/s) the continuous pumping method did not succeed at a pressure in the vessel of P=450kPa. However, the percussion method succeeds even at a vessel pressure of P=330 kPa. This demonstrates that the percussion method is dominant in some cases.

In fine sand both methods work well, with no significant difference in upheave being observed. As was the case with medium sand, a higher pressure in the vessel was required if the percussion method was applied. In both techniques a slightly higher pressure was required than was the case for medium sand.

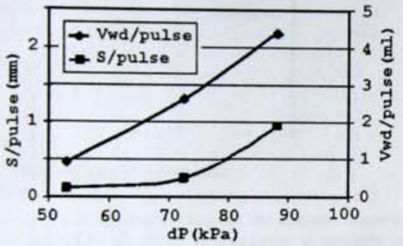

Fig.9 Percussion tests in fine sand at different pressures.

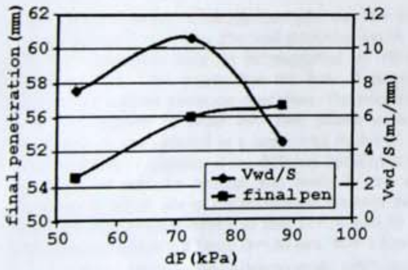

Fig.10 Relationship between pressure difference, final penetration and water consumption per mm.

A series of tests were carried out in fine sand to examine the influence of the pressure difference during installation by percussion (Fig.9). It was found that the water consumption increases almost linearly with pressure. The displacement, S, per pulse is increasing significantly after a pressure difference of approximately 70 kPa. Fig. 10 shows the final penetration and the water consumption per mm displacement. It appeared that at pressure differences lower than 70 kPa full penetration did not occur and the water consumption per mm increased with increasing pressure. At higher pressure full penetration was achieved more close and the water consumption per mm displacement decreased.

INSTALLATION IN COARSE SAND

In coarse sand (k=0.06 cm/s) it was not possible to install the pile with the continuous pumping method at the maximum vessel pressure of P = 450 kPa. A displacement of only 12 mm (16% of pile length) could be achieved. In this case the simulated pumping capacity could create a pressure difference of dP = 20 kPa, which was not sufficient to overcome the friction soil/pile. Fig.11 shows the parameters obtained during installation by percussion method.

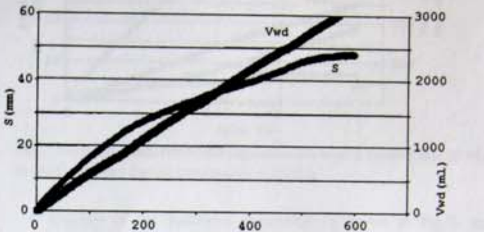

Fig.11 Graphical presentation of pile displacement, S, and water consumption, Vwd, during installation by percussion.

The vessel pressure was 400kPa and the pulse duration was 50ms. It appeared that the percussion method resulted in full penetration of the pile. The reason for the success of the percussion technique is probably the difference in behaviour of the soil plug. During continuous pumping, friction reduction is obtained by local fluidization along the boundary. Since the fluidization takes an appreciable time, sufficient pumping capacity is required. In the case of percussion the entire sand plug is lifted at once for a short period, resulting in friction reduction.

In Fig.12 the pulse duration is varied and the displacement per pulse is measured over a similar depth. It can be seen that displacement per pulse increases with increasing pulse duration for short pulse durations. At pulse durations of more than 160ms, however, little additional displacement is achieved. The reason is probably that the transition point to continuous pumping has been reached. It appeared that the pressure in the vessel (P_{out}) has little influence on the transition point. Fig.13 presents the water consumption per pulse. This relationship is almost linear with pulse duration, and the pressure P_{out} seemed to have little influence. Combining Fig.12 and Fig.13 it can be concluded that the optimum pulse duration lies between 50ms and 150ms.

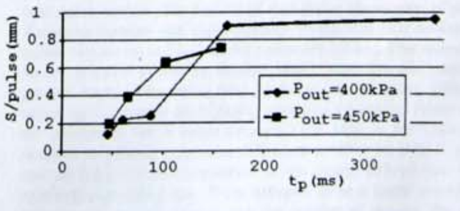

Fig.12 Relation between settlement, S, per pulse and the pulse duration t_p.

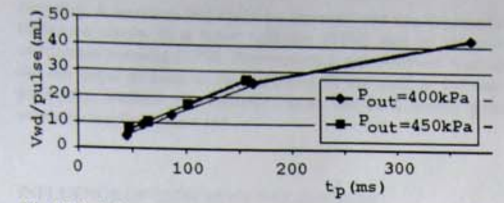

Fig.13 Relation between water consumption and pulse duration.

Table 1 Final pile penetration (% of full height) with continuous and percussion installation method, using piles with different dimensions.

D [mm]	H [mm]	W [mm]	cont [%]	perc [%]
30	82	1.5	77	86
40	73	1.6	82	87
50	92	1.3	91	95

SLENDER PILES

Some tests were performed to examine the influence of the geometry of the piles on the installation method. For a better demonstration of the differences between the two installation methods the wall of the piles are also thick in relation to the prototype situation in these tests. In Table 1 the final penetration in percentages of the full height are presented. The most slender pile used has a wall thickness of W = 1.5 mm and H = 82 mm; D = 30 mm (H/D=2.7). At smaller diameters both installation methods failed to result in full penetration because of upheave of the soil plug. It appeared, however, that the percussion method gives better results. In the case of the most slender pile the penetration was 86% of the maximum value, where 77% was measured for the continuous pumping method. In the case of the medium-sized pile (H = 92 mm; D = 50 mm) the penetration was 91% and 95% for the continuous and percussion methods, respectively. Tests with a third pile with intermidiate dimensions show a similar difference. It can be observed that the upheave increases with decreasing pile diameter. Furthermore the tests show the tendency that the percussion method is more effective at smaller diameters than the continuous method.

DISCUSSION AND CONCLUSIONS

Centrifuge tests have been carried out to investigate the performance of percussive suction placement of piles under a wide range of conditions. The aim of the tests was to ascertain the ability of the new technology to enlarge the field of application of suction placement of piles. As penetration problems were rarely encountered with the continuous method in sandy soils, the first series of tests were performed in fine, medium and coarse sand, respectively.

The results obtained in fine and medium sand did not show significant differences. Full penetration was achieved with both methods. However, the percussion installation proceeded more slowly and more water was pumped out from the model as a result of the repeated inflow of groundwater that is inherent in the method.

It was revealed that in the case of less initial penetration of the model into the sand, the percussion method appeared to be less susceptible to piping.

In coarse material the percussion method resulted in penetration of the pile, where the continuous method failed. There was found to be an optimum pulse duration if the displacement per pulse and water consumption were considered (in coarse sand 163ms for P_{out}=400kPa and 102ms for P_{out}=450kPa). On the other hand, the final penetration appeared to be better at smaller pulse durations, though the differences are small.

Tests with small diameter models have shown that the percussion method resulted in deeper penetrations than those reached with the continuous method, although some upheave was observed.

It remains unclear how much detail of the centrifuge tests can be translated to full scale tests. The process is dynamic and a combination of mass transport, groundwater flow and inertia forces. Different scale rules apply to the different physical phenomena, which indicates that care is required in the interpretation of the tests. It is believed, however, that the general tendency is realistic. For a better comparison it would be interesting to perform a full scale test.

The test procedure is fairly complicated and several parameters play a role in the installation process. This research set out to form an overall view of the parameters that are relevant in the installation process. More tests, however, are required in order to obtain more detailed information on the effect of each parameter.

The results of this first series of tests indicate that this novel method of installation will contribute to a wider field of application for suction piles. This has prompted continuation of the research to include layered soils and clay.

REFERENCES

Allersma, H.G.B. (1994), "The University of Delft geotechnical centrifuge", *Int. Conf. Centrifuge94*, Balkema, Rotterdam, pp. 47-52.

Allersma, H.G.B., F.J.A. Plenevaux, J,-F.P.C.M.E. Wintgens (1997), "Simulation of Suction Pile Installation in Sand in a Geocentrifuge", *7th. Int. Offshore and Polar Eng. Conference, ISOPE97*, Vol. 1, pp. 761-765.

Allersma, H.G.B., A.A. Kirstein, R.B Brinkgreve, T. Simon (1998), "Centrifuge and numerical modelling of horizontally loaded suction piles", *9th. Int. Offshore and Polar Eng. Conference, ISOPE99*, Vol. 1, pp. 711-717.

Allersma, H.G.B., J. Hogervorst, C. Dufour, 2000, Orientation tests on suction pile installation by the percussion method. Proc. of ETCE/OMAE2000, New Orleans, February 14-17, CD-ROM ASME paper no: OMAE2000/OSU OFT-4036.

El-Gharbawy, S. R. Olson (1998), "The pullout capacity of suction caissons foundations for tension leg platforms", *Proc. 8th Int. Offshore and Polar Eng. Conf.*, Montreal, pp.531-536.

Narasimba Rao, S., R. Ravi (1997), "Pullout behaviour of model suction anchors in soft marine clays", *Proc. 7th Int. Offshore and Polar Eng. Conf.*, pp. 740-744.

Senpere, D. and G.A. Auvergne (1982), "Suction anchor piles- A proven alternative to driving or drilling. *Offshore Technology Conference, OTC4206*, pp. 483-494.