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Observation of unexpected phenomena in geotechnical centrifuge tests

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INTRODUCTION

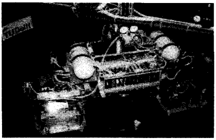
In the course of the past decade, a large number of small-scale tests have been carried out in the small geotechnical centrifuge of the University of Delft, on a variety of geotechnical problems. In the centrifuge testing technique, the soil samples are subjected to stress conditions similar to those experienced at full scale. This guarantees a more realistic behavior of the small models. An additional advantage of model tests is that the behavior of a structure can be monitored much more accurately than in a full-scale test. A small size centrifuge allows several tests to be performed in quick succession. This is particularly effective for the study of failure mechanisms and the influence of changes in design. Furthermore, it is possible to prepare small soil samples with precision, so that the effect of slight differences in design can be made visible. This has facilitated the observation of several unexpected phenomena, which are not yet predicted by mathematical models. Aspects of the following subjects will be discussed in this paper: behavior of conical footings; bearing capacity of suction piles; the installation suction pile; buckling of large diameter piles, buried pipes; widening of road embankments; cratering during gas blowout; slope stability, and failure of sand embankments during water infiltration.

TEST FACILITY

The centrifuge of the University of Delft

The geotechnical centrifuge at the University of Delft (Allersma, 1994a) was designed by the Geotechnical Laboratory of the Department of Civil Engineering and was built by the University's mechanical workshop. It is an example of a beam type centrifuge, and has two swinging carriers (Fig.1). A 1500 mm long beam is connected to the shaft, allowing it to be rotated in the horizontal plane. The two swinging carriers are connected to the beam by means of brackets. Each carrier consists of two plates held apart at a distance of 410 mm by four cylindrical steel connecting beams. The surface of a plate is 400 x 300 mm. Samples with a weight of 400N can be accelerated up to 300 g (12g-tons). The centrifuge is driven by an 18 kW electric motor through a hydraulic speed control unit. The hydraulic speed controller is manipulated by a stepping motor, which is interfaced to a PC. A computer program has been developed that adjusts the speed of the centrifuge using the signal from a tachometer. Several options are available for speed control. For example, it is possible to make the acceleration dependent on time, or on such test parameters as the pore water pressure in a clay sample.

The system electronics enable the performance of computer-controlled tests in flight (Fig.2). To minimize electrical disturbances, the control unit is placed in the spinning part of the centrifuge. The unit contains a small single board IBM-PC compatible computer (180x120x25mm; 486CPU; 66Mhz; 16Mbyte RAM; 32Mbyte ROM disk; 1 Gbyte hard disk; 1.44Mbyte floppy disk), a 12-bit analog to digital converter with a 16-channel multiplexer, two voltage controlled outputs of 8 amps each; two 16-bit counters and several digital inputs and outputs. The 1Gbyte hard disk is located at the precise center of the centrifuge, where it operates correctly up to at least 160g at 1 meter. The signals from the sensors can be read into a computer program via an analog to digital converter. The voltage controlled outputs are used for the proportional control of small DC motors, and the digital inputs are used to detect the rotation of pulse wheels in order to deduce displacements. The digital outputs can be used for on/off control of several devices, such as DC motors, electro-pneumatic valves, etc. Eight power slip rings are available for feeding the electronics and the actuators. 24 high quality slip rings are used to transmit the more sensitive signals, such as two video lines and the connection between the on-board computer and the keyboard and monitor in the control room (10 lines). The on-board computer is accessible in the same way as a normal PC. During a test, the relevant parameters are displayed in graphical form and stored in the solid state disk unit or the hard disk. A special feature is that several phenomena can be measured using the video images. In this technique the video images of the in-flight test are captured by the frame grabber in the PC and processed until the relevant parameters



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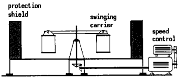

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Fig1 a) Photograph of the small centrifuge of the University of Delft. b) Schematic drawing.

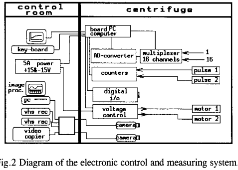


Fig.2 Diagram of the electronic control and measuring system.

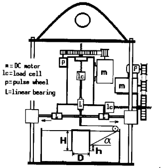
are isolated and digitized. Image processing can be used to visualize and digitize the surface deformation of clay and sand samples, to digitize the consolidation of a clay layer or to digitize the displacement of objects (Allersma, 1990, 1994d). The use of light as a measuring medium ensures that the measurement does not influence the test in any way.

Devices for in flight tests

Several devices have been developed for the purpose of performing advanced tests in flight (Allersma, 1994). The two-dimensional loading system (Fig. 3a) can be considered to be a universal tool, with application in several tests. Adjustable vertical and horizontal displacements of 100mm and 200mm, respectively, can be achieved with an accuracy of better than 0.1mm. The loads are measured in the two perpendicular directions. The measured loads and displacements are used in a computer program to control the device. The system is able to apply loads in excess of 5 kN. In addition to loading tests, the device can be used as a simple robot to manipulate tests in flight or to take samples. An example of its use is the simulation of combined loading on shallow footings or the removal of struts of sheet pile walls in flight. An in-flight sand pouring machine (Fig.3b) with a width of 150mm is available to construct embankments in flight. The sand can be poured at a particular location or layer by layer over 150mm. The strategy can be defined in a computer program. The device can be used to simulate the widening process of embankments, for example.

Some tests require gas to be supplied to a soil sample. Because the small centrifuge is not equipped with fluid slip rings, the gas has to be stored in the spinning section of the centrifuge. To make the storage as compact as possible, two high pressure (200 bar) 5 liter cylinders are mounted on the centrifuge beam. A computer-controlled air supply system has been developed in order to regulate the pressure and the gas flow. Flow rates of 10 l/s can be achieved. The gas in the high pressure cylinders represents a considerable amount of power, which can be used, in principle, for tests calling for large loads or energy. The gas supply system is used for several tests, such as pile driving, water circulation, control trapdoor test, simulating gas blowouts in soil layers and simulation of a suction pile installation.

Other tools available to perform a large variety of in-flight tests include a pile driving hammer, in-flight excavation, wave simulator and pollution infiltration.



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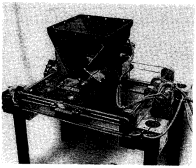

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Fig.3 In flight testing equipment a) two dimensional loading system, b) sand raining machine.

Sample preparation

An important aspect of centrifuge research is sample preparation. Samples of different soil types have to be prepared, in which the density can be varied. Comparison of the results of different tests is possible only if good reproducibility of the samples is achieved. An automated computer-controlled curtain rainer has been developed to prepare well defined sand layers in the test containers (Fig.4). The falling height of the sand can be adjusted in order to control the density. The height is kept constant during raining by means of an optical sensor and an actuator. Sand samples with a surface area of 300x300 mm and a maximum thickness of 150 mm can be prepared. The porosity can be varied between 35% and 39%. The sand samples can be reproduced with a standard deviation of less than 0.2 percent. The preparation of a sample with a thickness of 100mm takes about 20 minutes.

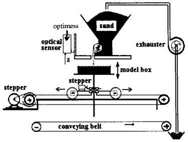


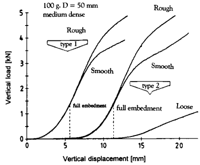
Fig.4 Computer controlled sand preparation device.

The preparation of clay samples is dependent on the type of test that has to be performed. In many cases pottery clay can be used. The small size of the models means that commercially available quantities are sufficient. In tests requiring normally consolidated clay, a slurry with a water content of more than 100% is consolidated at the desired g-level. This assures the most realistic water content and strength over the height. A special centrifuge is available for this task.

TEST RESULTS

Behavior of conical footings

The research on the behavior of conical footings was related to the



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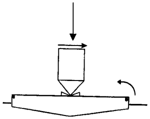

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Fig.5 Behavior of spudcan foundation during vertical (a) and horizontal (b) loading.

foundation of mobile offshore structures. The main goal was to examine the sliding behavior of shallow footings on sand, by simulating the loading path which is assumed to occur under storm conditions (Allersma et al. 1997a).

The test results have been used to examine the reliability of the design rules. A number of interesting phenomena could be observed in the test program on medium dense dune sand. Fig.5a shows a plot of the response of vertically loaded spudcans at 100g, where footings are used with and without tip and with different surface roughness. The non-linear course of the first part of the curve clearly shows the influence of the conical shape of the footing. It appeared that roughness had no significant influence on the course in the first part. The final bearing capacity was not reached at full embedment. An extra displacement of about 0.05 times the diameter was required. The roughness of the footing was varied by using a smooth metal surface and a surface of sandpaper. The graphs show that the roughness significantly affects the vertical bearing capacity (more than 20%). It was found that the horizontal sliding resistance of a rough cone was 28% more than a smooth spudcan. Increasing roughness seems to be an inexpensive way to improve the bearing capacity of spudcans.

The influence of the tip is also visible. In the case of smooth spudcans, the bearing capacity of footing with tip is 14% lower than the footing without tip. In the tests with the rough surface the difference is 7%. Apparently the tip disturbs the soil somewhat, resulting in lower vertical bearing capacity. On the other hand, the tip increases the horizontal bearing capacity significantly. In the case of a smooth or rough cone an increase of approximately 25% could be observed (Allersma, 1997b).

In Fig.5b, a horizontal loading test was performed on a vertically loaded spudcan, where a free rotation of the footing was possible. A surprising phenomenon was that the footing rotates counter clockwise. In Fig.6, the principal stress trajectories are made visible in a centrifuge test by using optically sensitive granular material (Allersma, 1987, 1998). It can be seen that the major principal stress rotates as a result of the horizontal components (Fig.6b). The stress rotation indicates that a counterclockwise rotation of the footing is to be expected.

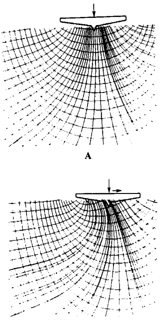


Fig. 6. Measured principal stress trajectories. a) Vertical loading, b) Combined horizontal and vertical loading. The diameter of the footing is 50 mm (5 meter prototype at 100g).

Bearing capacity of suction piles

Suction pile foundations are recognized as an effective method for anchoring floating devices and to fix offshore structures to the sea floor. In particular the installation of suction piles is attractive, because only a pump is required to penetrate, for example, a pile with a height of 10 meters and a diameter of 9 meters in a few hours into the sea floor.

In the case of anchoring of floating devices, the anchor is often loaded in the horizontal direction. A test program has been carried out (Allersma, 1999a) to examine the horizontal bearing load in relation to several conditions, such as the loading angle, pile height and diameter. The need to save material, led to the invention of a pile whose top lies below the sea floor (Fig. 6). In soft clay in particular, the upper part of the pile does not contribute much to the bearing capacity. The installation should occur by a pile segment with a dome, which can be recovered after the installation process. In order to examine the effect of this installation technique, a series of centrifuge tests were carried out on piles installed at the same depth, but with different

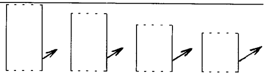


Fig. 6 Diagram of the position of suction piles below sea floor

height. An unexpected result was that the horizontal bearing capacity increases with decreasing length of the piles. If the height of the pile was reduced by 30%, the bearing capacity increases by approximately 25%. The effect was less strong in clay, but increased bearing capacity could be observed nonetheless. It was found that the bearing capacity was also larger in the case of pure vertical pullout load. The reason for the increasing bearing load is probably that, in the case of a full size pile, friction occurs along the pile wall. If the pile is below sea floor, friction is generated in the soil, apparently resulting in larger pullout loads.

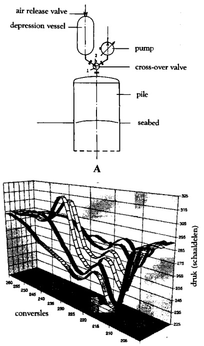


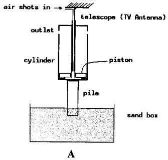
Fig.7 a) Diagram of device to install suction pile by percussion. b) typical output of the first 5 pulses (from right to left).

Installation suction pile

The installation of suction piles is based on generating a pressure difference between the interior of the pile and the outside water mass by means of a pump. The pressure difference causes a vertical load, being the driving force to penetrate the pile into the soil. However, after penetration over some distance in the soil, the friction between pile and soil becomes so great that further displacement would not be possible. The friction causes a larger pressure difference between the inside and outside of the suction pile. In sand, the pressure difference initiates a vertical upward groundwater flow, which reduces the effective vertical stress in the soil plug. This results in friction reduction so that further penetration can be achieved. In common soil types, the installation proceeds without problem. Simulation in the centrifuge shows that the relationships between the pressure difference and the geometrical dimensions were almost linear (Allesma et al., 1997c). However, problems can occur in the case of course material, layered soil, an uneven sea floor and where slender piles are used. In order to improve the installation process in more difficult circumstances, a new installation method was proposed in which the pile is installed by the percussion method. Instead of a pump, a vacuum chamber was connected to the suction pile (Fig.7a). The pile can be subjected to short pressure shots by means of a valve. The installation method has been simulated in centrifuge tests at 50g. An example of a series of shots is shown in Fig.7b, where the sequence is from right to left. Typical phenomena are that the under-pressure peaks are lower in the first instance. This is a consequence of the low resistance of the pile at the start. The wave nature of the development of the pressure in time is characteristic. It demonstrates the second order character of the system. The over-pressure peak of the third and fourth pulse is caused by the motion of the pile after the valve has been closed. The over-pressure peak decreases at a later stage because increasing friction prevents pile motion after the valve closes. The most surprising result was the difference in water consumption during installation. It was found that the installation by percussion reduces the water consumption by a factor of 10 (excluding the volume of the pile). This is an interesting phenomenon in cases with course material, where the installation can be hampered by limited pump capacity. The lower water consumption is also assumed to be an advantage in the case of an uneven sea floor.

Buckling of large diameter piles

Hollow cylinder, large diameter piles (e.g. D=2.40m, 40mm wall thickness) were used in a project to fix an offshore production platform at the sea floor. Because the sub-soil (at approximately 100m) was too cohesive for pile driving and the first 100m too soft for yielding enough pull out resistance, it was decided to drill through the hollow cylinder piles into the cohesive layer. After all the piles had been driven into the soil, the plan was to start drilling. However, it soon appeared that almost all the piles had collapsed by buckling over a length of approximately 30m, starting from the tip. Looking at the tip side, a so-called peanut shape could be observed. Several reasons, including the presence of boulders, and inclined calcareous layers, were proposed to explain the collapse of the piles. The installation process was simulated in the centrifuge by using a miniature pile driving device (Fig.8a). In order to simulate the prototype piles, piles with a diameter of 12mm and wall thickness of 0.4mm were driven into the soil at an artificial gravity of 150g.



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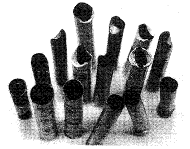

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Fig. 8 In flight pile driving machine (a) in order to simulate failure by buckling (b) during driving.

An interesting observation was that the proposed mechanism, e.g. based on inclined calcareous layers, did not give rise to buckling in the centrifuge tests. However, it appeared that buckling could be produced, but only if a small initial damage was generated at the pile tip.

Buried pipes

The aim of this test program was to examine whether the uplift capacity of buried pipes changes under cyclic loading conditions. The fear was that cyclic loading would decrease uplift resistance, so that the estimates of the thickness of the cover layer were too low. Cyclic loading was assumed to be affected by buckling of the pipe as a result of thermal effects. In the first instance, the static pullout capacity was determined. Next a pipe segment was subjected to cyclic loading starting with a maximum of 80% of the static pullout load. If no displacement could be observed the maximum load was increased. A typical diagram is shown in Fig.9. It was found that cyclic loading did not decrease the pullout load significantly. On the contrary, it was possible to observe a tendency for the pullout load to increase, which is probably caused by densification of the sand during the cyclic loading.

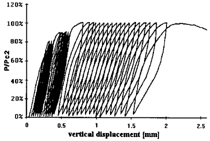
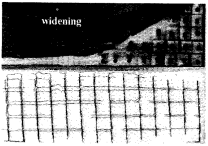


Fig.9 Load-displacement diagram of buried pipeline under cyclic loading.

Widening of a road embankment

Several tests have been carried out to examine the behavior of existing sand embankments on soft soil during its widening (Allersma et al., 1994c). The aim of the research program was to examine the mechanism that causes cracks in the asphalt pavement. The extent to which the sand supply scheme influences the cracking behavior of the asphalt layer was also investigated. A typical set of test results is shown in Fig.10a. The deformation of the clay after widening is made visible by grid lines, where markers are used to make the behavior of the existing embankment visible. It is clearly visible that there are no significant horizontal displacements. This means that this cannot be the reason for cracks in the asphalt. However, a gradient in the vertical displacement can be observed underneath the embankment. Thanks to this gradient, the embankment is subjected to bending, which causes tensile stresses in the asphalt cover. It can be deduced that a gradient of only a few degrees can cause cracks of 100 to 200mm. Vertical displacement of the asphalt cover were also observed in some cases in the field. This observation could give the impression that a more complicated deformation mechanism is



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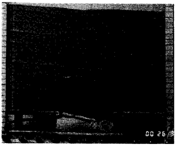

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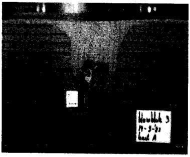
Fig. 10 a) Widening of embankment on soft clay. b) Simulation of a displacement gradient in sand.

active in the clay layer. In Fig.10b, however, it is shown that abrupt vertical displacement in a sand layer is possible at some distance from the source, even when the source causes only a gradient in vertical displacement.

Cratering during gas blowout

A gas blowout can occur during the drilling process. Fracturing can allow a loss of the mud used to keep the pressure of the reservoir under control. A mixture of gas and oil can reach the surface, causing a crater of fluidized soil (Fig.11). This may result in loss of equipment (Fig.11a), or in triggering a chain reaction where there are other wells in the vicinity.



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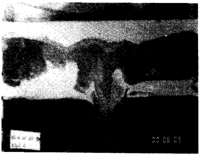

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Fig.11 Examples of gas blowouts a) sinking material; b) clay layer in sand.

In order to form a view on the depth of the crater, gas blowouts were simulated in sand layers at 150g in the centrifuge (Allersma et al., 1994e). The gas was introduced at the bottom of the sample. It first appeared that a rather sudden start was required to create a crater at all. However, if an element was also placed at the surface, a crater was formed under conditions of a gradual increase in gas flow. The tendency was observed in the field that the crater bottom did not pass clay layers. However, in centrifuge tests it was observed that a clay layer causes a crater. The gas accumulates in the first instance under the clay layer, causing a sudden supply when it breaks through.

Failure of sand embankments during water infiltration

In order to gain a better insight into the failure behavior of embankments during wave overtopping, several test programs have been carried out in the centrifuge (Allersma, 1999). A model of a rather common construction of an embankment used for water protection is shown in Fig.12a. The embankment consists of a sand body which is covered with a clay layer at the land side. Since the water side of the embankment is in general covered with a waterproof layer (e.g. asphalt), water infiltration occurs through cracks in the clay layer during wave overtopping. In the centrifuge test at 80g, water is infiltrated at the crest of the dike. The two-dimensional model in combination with transparent boundaries allowed the rise of the groundwater table to be observed. Furthermore, the stream lines have been made visible by means of a tracer. A surprising observation was that no shear band failure mechanism could be observed. Should the embankment be constructed of pure sand, failure starts at the toe, which is visible as gradual erosion as a result of seepage. If the sand embankment is covered with a clay layer, the increasing pressure during water table rising tilts up the clay cover (see stream lines in Fig.12a). This causes friction reduction resulting in cracking of the clay layer under its own weight. The location of the crack appeared to be dependent on the thickness of the clay layer. The larger the thickness, the higher the crack. In practice, the first crack is usually formed at the transition between slope and crest. Once the crack is there, water will erode the embankment more easily. Fig.12b shows the result of a field test on an embankment construction similar to that used in the centrifuge. In this test wave overtopping was simulated by running water over the slope surface. The surface deformation was made visible by placing labels at the slope surface and by subtracting photographs of two different stages.

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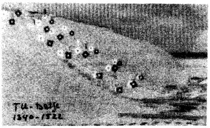

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Fig.12 Simulation of embankment failure a) centrifuge test; b) field test.

It was also visible in this test that motion of the clay layer is mainly parallel to the slope surface. In this case, the crack was close to the crest, where some buckling can be observed at the toe of the embankment (caused by water pressure). Afterwards, a cut was made in the embankment in order to examine whether shear band failure could be visualized. However, even with the help of clay columns, no shear bands could be identified.

CONCLUSION

A number of tests have been carried out in the small centrifuge in order to examine a variety of problems. The small centrifuge has been found to be very convenient for trial and error tests. The small models could be modified easily, and several tests could be performed in a short period. Thanks to this, several different conditions could be examined in a modest amount of time, and at a very reasonable cost. In several cases, surprising phenomena have been observed, which could not easily be deduced from exercises with mathematical models. On the other hand the centrifuge tests were helpful in validating analytical and numerical calculations.

The centrifuge tests were helpful in understanding the soil (structure) behavior. In several cases only centrifuge tests were able to get a better insight into the problem. Some test results are used directly in engineering practice and for improving the monitoring strategy in field tests.

REFERENCES

Allersma, H.G.B. 1987: Optical analysis of stress and strain in photoelastic particle assemblies, Thesis, Delft University of Technology, Delft, the Netherlands.

Allersma, H.G.B. 1990: On line measurement of soil deformation in centrifuge tests by image processing. Proc. Int. Conf. on Experimental Mechanics, Copenhagen, pp. 1739-1748.

Allersma, H.G.B. 1994a: The University of Delft geotechnical centrifuge. Proc. Int. Conf. Centrifuge94, Singapore, Balkema Rotterdam, pp. 47-52.

Allersma, H.G.B. 1994b: Development of miniature equipment for a small geotechnical centrifuge. Transportation Research Record No. 1432. Nat. Academy Press, Washington D.C., pp. 99-105.

Allersma, H.G.B., L. Ravenswaay and E. Vos, 1994c. Investigation of road widening on soft soils using a small geotechnical., Transportation Research Record No.1462, National Academic Press Washinghton, D.C. pp. 47-53.

Allersma, H.G.B., H.G. Stuit, P. Hölscher, 1994d: Using image processing in soil mechanics. Proc. XIII Int. Conf. on Soil Mechanics and Foundation Eng., New Delhi, pp. 1341-1344.

Allersma, H.G.B., W.J. van Niekerk, A.P. Kooijman, 1994e: Simulation of cratering in a small geotechnical centrifuge. Int. Conf. Centrifuge94, Singapore, Balkema Rotterdam, pp. 325-330.

Allersma, H.G.B., B. Hospers, J.G. den Braber, 1997a: Centrifuge tests on the sliding behaviour of spudcans. Canadian Geotechnical J., 34(5), pp. 658-663.

Allersma, H.G.B. 1997b: Centrifuge tests on the influence of shape on the sliding behaviour of spudcans. Proc. Int. Conf. Behaviour of Offshore structures, Delft, the Netherlands, pp.225-233.

Allersma, H.G.B., F.J.A. Plenevaux and J.F. Wintgens 1997c: Simulation of suction pile installation in sand in a geocentrifuge. Proc. 7th Int. Offshore and Polar Eng. Conf., Hawaii, May, Vol. 1, pp. 761-766.

Allersma, H.G.B., 1998. Stress analysis on photoelastic particle assemblies in centrifuge tests. Int. conference Centrifuge98, Tokyo, Sept.23-25, 1998, pp.61-67.

Allersma, H.G.B., 1999. Centrifuge tests on slope failure during water infiltration. Int. Symp on Slope Stability Engineering (IS-SHIKOKU'99). Matsuyama, Japan, Balkema, pp.447-452.

Allersma, H.G.B., A.A. Kirstein, R.B.J. Brinkgreve, T.Simon, 1999a. Centrifuge and numerical modelling of horizontally loaded suction piles. 9th Offshore and Polar Eng. Conference, Brest, pp.711-717