Possibilities of small geotechnical centrifuges

Possibilités des petites centrifugeuses géotechniques

Henderikus G. B. Allersma – *Delft University of Technology, Netherlands*

SYNOPSIS: A small centrifuge has been developed at the geotechnical laboratory of the University of Delft. The dimensions have been chosen in such a way that it is believed that an optimal ratio is obtained between possibilities and convenience of operation. Several topics can been tested, such as; embankments and their widening; sliding behaviour of shallow footings, wave overtopping, buckling of large diameter piles, gas blowouts, trapdoor problem, suction pile installation, pile driving, pollution transport. The convenience of operation is demonstrated by the fact that several tests on different topics can be performed on the same day.

1 INTRODUCTION

Centrifuge research (e.g. Leung et al., 1994) has proved to be effective in investigating the behaviour of soil and other granular materials. With this technique it is possible to use scale models to visualize the behaviour of large scale problems. Clay is a typical example of a material with a strong stress dependent behaviour but also materials like sand behave differently under different stress levels. If tests are performed on small samples of for example wet sand, the results are strongly influenced by capillary pressure because the cohesion caused by this pressure is of the same level as the interparticle stresses. In most practical problems the stress dependent behaviour has to be taken into account in order to make reliable predictions.

The tendency has been to increase the size of the centrifuges in order to model more details. For several geotechnical problems, however, the use of a small centrifuge is quite adequate. By making an optimal choice between size and facilities and using up-to-date electronics and computer control, advanced tests can also be performed in a small centrifuge. A small device is cheap in operation, and the development of the equipment did not take so long compared with a large centrifuge.

A geotechnical centrifuge with a diameter of 2.5m has been built at the Geotechnical Laboratory of the University of Delft. To enable the performance of advanced tests in flight, the carriers of the centrifuge were made large enough to contain computer-controlled devices. The test containers and actuators are, in general, so small that they can be conducted by one person. This is convenient during the preparation of the tests and leads to good reproducibility of the soil samples. Thanks to the low weight modification of the centrifuge for different tests is simple, so that a flexible operation is obtained. A disadvantage of a small centrifuge is the limitation in the use of sensors during a test. This restriction, however, can be compensated by processing of images taken with the on-board video camera. Miniature devices have been developed for performing advanced tests in flight, such as: loading, displacement and controlling the flow of sand, water and air. The devices operate under the control of software, which runs in a computer located in the spinning part of the centrifuge.

To improve the reproducibility, sample preparation is automated as much as possible. A special centrifuge has been built to consolidate clay slurry, in order to obtain a very soft normally consolidated clay. Several research projects have been carried out in the centrifuge, e.g.: sliding behaviour of spudcan foundations, stability of dikes during water infiltration, gas blowouts and cratering, stability of embankments during widening, suction pile installation, trapdoor, buckling of large diameter piles, pile driving, shear band analysis. The flexibility of the centrifuge is demonstrated by the fact that three quite different model tests can be performed on the same days.

2 THE SMALL CENTRIFUGE

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 mechanical workshop of the University. The electronic systems were designed and built by the Geotechnical Laboratory. The advantage of an in-house design is that a very flexible operation of the device is possible. The system can be expanded and modified under own supervision, thus guaranteeing a good interaction between the facilities of the device and the tests.

2.1 *Mechanical construction*

The centrifuge is a so called beam type centrifuge with two swinging carriers. The centrifuge frame is fixed to the floor and bears the vertical axis and the protection shield (Fig.1). A beam with a length of 1500 mm is connected to the axis, so that it can be rotated in the horizontal plane. Two swinging carriers are connected to the beam by means of brackets. The carriers are formed by two plates at a distance of 410 mm apart, which are connected to each other by four cylindrical steel beams. The surface of the plates is 400 x 300 mm. Samples with a weight of 400N can be accelerated up to 300 g. The centrifuge is driven by an 18 kW electric motor via a hydraulic speed control unit. The hydraulic speed controller is manipulated by a step motor, which is interfaced to a PC. A computer program has been developed to adjust the speed of the centrifuge using the signal of a tachometer. Several options are available to control the speed. It is, for example possible to make the acceleration dependent on time or on test parameters, such as the pore water pressure in a clay sample.

2.2 *Electronic facilities*

The system electronics enable the performance of computer-controlled tests in flight (Fig.2). To minimize electrical disturbances, the control unit is

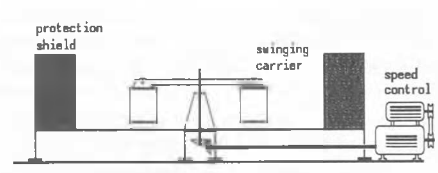

Fig.1 Diagram of the small centrifuge of the University of Delft.

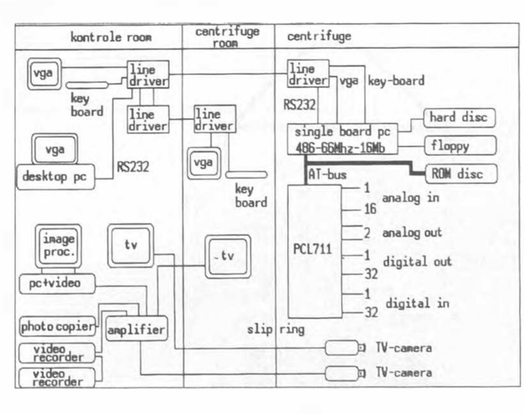

Fig.2 Diagram of the electronic control and measuring system.

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 Ampere each; two 16-bit counters and several digital inputs and outputs. The 1Gbyte hard disk is placed just in the centre of the centrifuge and operates correctly up to at least 160g at 1 meter.
The signals from the sensors can be read in a computer program via a analog to digital converter. The voltage controlled outputs are used for proportional control of small dc-motors, where 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-motor, electro/pneumatic valves, etc. Eight power slip rings are available to feed the electronics and the actuators. 24 high quality slip rings are used to transmit the more sensitive signals, such as, for example, two video lines and the connection between the on-board computer and the key-board and monitor in the control room (10 lines). 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 are isolated. Image processing can be used to visualize and digitize the surface deformation of clay and sand samples or to digitize the consolidation of a clay layer (Allersma, 1990, 1994f). This technique has proved to be very useful in several research projects.

3 DEVICES FOR IN FLIGHT TESTING

Special devices have been developed in order to perform advanced tests in flight. The major devices are described briefly. Several other devices are available to control tests, such as: pile driving hammer, water circulation system, vane apparatus, in flight pressure vessel. For more details see (Allersma, 1994b).

3.1 *Two dimensional loading system*

The two dimensional loading system (Fig. 3) can be considered as a universal tool, which can be used for several tests. The system is driven by two miniature dc-motors. The displacement is measured by means of small pulse generators. A vertical and horizontal displacement of 100mm and 200mm can be adjusted, respectively. The accuracy is better than 0.1mm. The loads in the two perpendicular directions are measured. The measured loads are used in a computer program to control the device. Loads of more than 5 kN can be applied by the system. Exept for loading tests the device can be used as a simple robot to manipulate tests in flight or to take samples. Up to present the device has been used at gravitation levels of more than 150 g.

3.2 *Air supply system*

In some tests it is required that gas can be supplied to a soil sample. Since 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) cylinders of 5 litres each are mounted on the beam of the centrifuge. 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 in which large loads or energy are needed. The gas supply system is

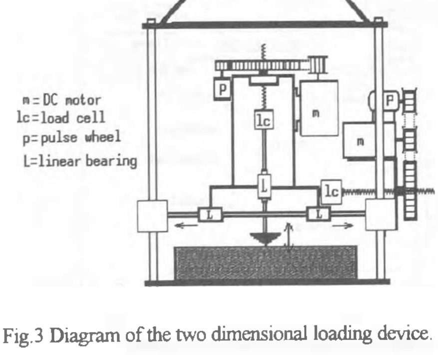

Fig.3 Diagram of the two dimensional loading device.

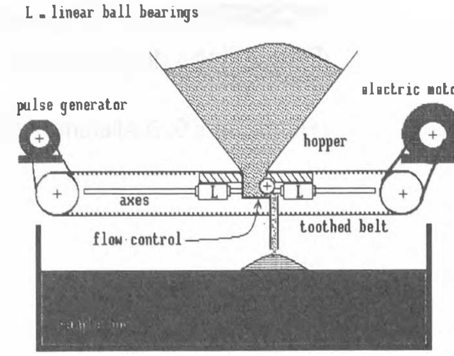

Fig.4 Diagram of the in flight sand pouring machine.

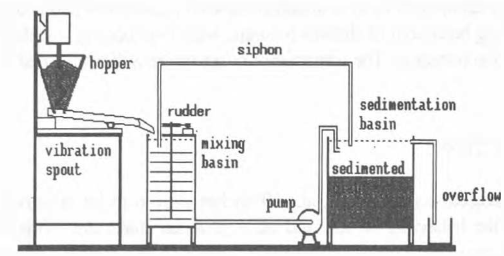

Fig.5 Diagram of the slurry preparation device.

used for several tests, such as: pile driving, water circulation, control trapdoor test and for simulating gas blowouts in soil layers.

3.3 *Sand pouring machine*

A computer controlled sand pouring machine has been developed in order to make embankments in flight. The device consists of a hopper, which can be translated (Fig. 4). The translation range is 150mm. The position of the hopper is detected by means of a pulse wheel. The sprinkler system is designed in such a way that no tight seals are required. Several options can be assessed in the control program. It is possible to sprinkle sand layer by layer or at one particular location. At 100 g embankments with a prototype height of more than 6m can be constructed at a clay layer with a prototype thickness of more that 12 meters. The sand pouring system is used to investigate the stability of dikes, and different methods of widening embankment, founded on soft soils are tested.

4 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. To enable the results of different tests to be compared, a good reproducibility of the samples is required. Two different devices have been developed for preparing accurately clay and sand layers.

4.1 *Clay preparation*

Up to now it has been found that the best control over the samples was obtained by making artificial clay. In this technique clay powder is mixed with water, where the air content is kept as low as possible. A technique has been developed in which an air free slurry is obtained under normal atmospheric pressure. The principle of the device is that the clay is added in a thin layer to a rotating water surface (Fig.5), so that no air is included because of differences in capillarity. The water with a very low clay content is pumped into a basin were the clay is sedimented.
Soft, normally consolidated clay is obtained to consolidate the slurry in the centrifuge at the same g level as will be used in the tests. Since the centrifuge will be occupied all that time no other tests can be performed. Therefore, a special centrifuge that is used only to consolidate the clay layers has been built. The properties of the clay is measured in flight, by a vane apparatus.
The deformations in tests are measured by means of a grid at the soil surface. In order to reduce the possible disturbances a method has been developed in which a grid can be copied to the clay surface without removing boundaries. The deformation of the grid is observed in flight by a CCD camera, were the displacements of the nodes are digitized by means of image processing.

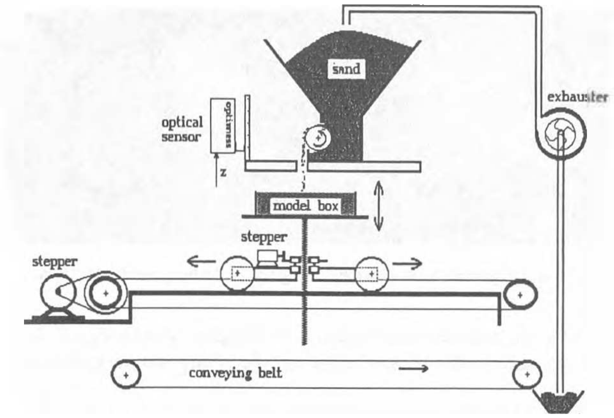

Fig.6 Diagram of the automated sand preparation device.

4.2 Sand preparation

An automated computer controlled curtain rainer has been developed to prepare well defined sand layers in the test containers (Fig.6). 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 made. 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 the sample with a thickness of 100mm takes about 20 minutes.

5 APPLICATIONS

Tests have been carried out in order to analyze several different geotechnical phenomena. For most geotechnical simulations, many tests are required to get a better insight into the problem. The special feature of a small centrifuge is that the tests can be performed in a relatively short period. Since it is not possible to describe all the tests in detail, only the major tests are discussed.

5.1 Stability of embankments on soft clay during widening

In several cases there is a need to widen embankments of sand on soft clay. The embankment can be the foundation of a road. As a result of deformations during widening, cracks can originate in the asphalt pavement. It was observed in the field that the intensity of the cracks tended to be dependent on the widening procedure. The widening can be made layer by layer, where the time interval between the suppletion is dependant on the pore water pressure. Furthermore, the so called gap method can be used, where an embankment is first built at some distance from the initial embankment and then the gap between the two embankments is filled. In general the field conditions are so complicated that it is not easily possible to investigate this problem in real scale tests. In a centrifuge, a reproducible soil layer can be prepared and the time intervals and test procedure can easily be varied simply. In Fig.7 it is shown by means of image processing how the grid and markers are displaced during the different widening methods. In both methods it seems that the horizontal displacement is very slight. The only difference between the test is the gradient in vertical displacement under the existing embankment. Since the difference between different widening methods is very slight, accurate tests and measurements have to be performed to visualize the deviations.

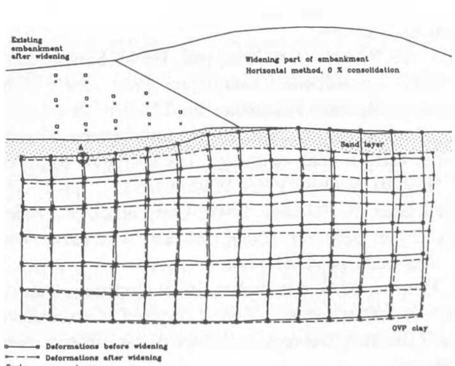

Fig.7 Deformation during widening test, digitized by image processing.

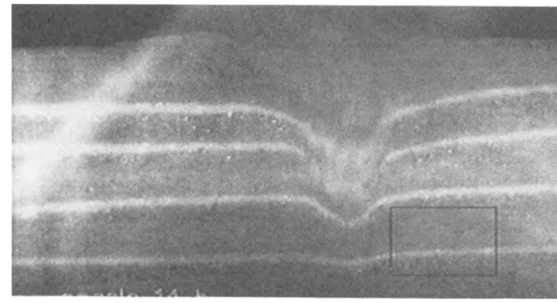

Fig.8 Simulation of a gas blowout in sand at 150g.

It could be shown that a gradient of a few degrees can cause cracks at the surface (Allersma et al., 1994e). The tests show that the gap method results in smaller gradients.

5.2 Simulation of cratering due to gas/liquid flow

A human made crater can occur during drilling to gas/oil reservoirs. If the control over the pressure is lost at the moment that the cover of the reservoir is penetrated an internal blow-out occurs. Because of accidental canals the escaped fluid and gas is able to reach the surface. If the flow is strong enough, a crater with fluidized soil can be formed, which can, for example cause the drilling installation to sink down. A chain reaction can be initiated in the case that neighbouring production pipes enter the crater zone. Therefore safety valves are installed in many cases. A prediction has to be made about the installation depth. The formation of a crater is a complicated process, which cannot be described simply by analytical or numerical models. Therefore tests are the only possibility for aquiring more insight into this phenomenon. Since it is almost impossible to perform field tests small scale tests are the only way to study the mechanism. Small scale tests at 1g are not realistic, because the capillary cohesion influences the results significantly. In a centrifuge, the own weight stresses are increased, where the capillary cohesion remains the same. To enable visualization of the process several tests are performed under plane strain conditions. Sand layers with a maximum height of 40 m are simulated. The gas pressure and flow rate can be adjusted in flight. In Fig.8 a test result is presented in a sand layer. Some typical results are (Allersma et al., 1994d):

- A crater is formed mainly when the gas supply is started abruptly.
- A clay layer also initiates a crater at a gradual gas supply, because the gas accumulates in the first instance under the clay layer, where the sudden escape simulates an abrupt supply.
- Also a foundation element causes a crater at a gradual gas supply.

5.3 Simulation of water infiltration in dikes by wave overtopping

Wave overtopping causes water to run over the slope on the land side of a dike. Since the slope on the land side is not protected against water infiltration, the freatic line in a sand dike rises. At some moment local failure occurs, which can finally lead to complete failure of the dike. Although this

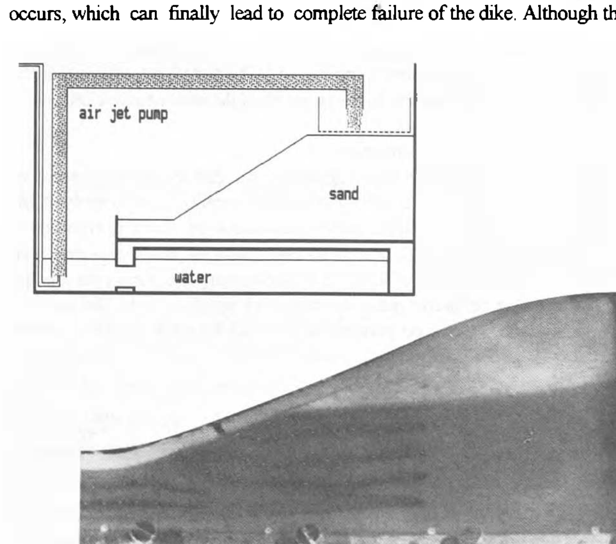

Fig.9 a) Diagram of the air jet pump. b) Failure of a sand slope, covered with clay, resulting from water infiltration at the crest.

phenomenon has taken place several times in practice it was still not clear what mechanism was active. In several cases the observations were made afterwards, so that the progress of the damage was not noticed. In advance of a real scale test a test program has been carried out in the centrifuge (Allersma et al., 1994c). The tests are carried out in a centrifuge in order to eliminate the influence of the capillary cohesion. A test setup as shown in Fig.9a is used to infiltrate a model of a two dimensional dike. A typical dike configuration is a sand body covered with a clay layer. The water infiltration is simulated by supplying the water at the crest of the dike. During the test the ground water table is visible and by means of grains of tracer material, the stream lines can be visualized. In Fig.9b it is shown how the direction of the stream lines changes when the ground water table increases. It could be observed that the increasing water table lifted up the clay cover. Since the friction between clay and sand body decreases the tensile forces in the clay cover increases, which finally causes cracks in the clay layer. It could be shown that the thickness of the clay layer, the shape of the sand body and the location of a drain influences the stability.

5.4 *Sliding behaviour of shallow footings*

Shallow footing (spudcans) are used for the foundation of mobile drilling platforms used offshore. If the spudcans are installed on clay the penetration depth of the footing due to the pre-load is approximately one diameter. In the case of sand, however, the penetration depth is much less, so that the foundation elements are more sensitive to sliding. To get more insight into the sliding behaviour several experimental research projects have been carried out in the centrifuge. By means of a two dimensional loading system the loading path which can occur during a storm is simulated. Good reproducibility of the samples (standard deviation in density better than 0.2%). is required if small changes in the shape of the footing or installation procedure are investigated. Most tests are carried out at 150g. Because dry sand was used, the stress gradient agrees with an acceleration of 240g if a prototype of saturated sand layer is simulated. A footing with a diameter of 6 cm is therefore equivalent to a prototype footing with a diameter of 14m. This is a realistic prototype dimension. The test results showed that one of the sliding checks as advised in the Recommended Practice for Site Specific Assessment of Mobile Units is applicable to restricted loading conditions and may therefore be unconservative (Allersma et al., 1996).
Several other foundation problems can be simulated in a small centrifuge. Some examples are: horizontal and vertical resistance of clock anchors (prototype dimension 9 metres height, 10 metres diameter); pile driving (the pile driving machine operates at 150g); buckling behaviour of large diameter hollow cylinder piles (2.6 metres diameter, length 30 metres); influence of shape on bearing capacity of shallow footings.

5.5 *Simulation of suction pile installation*

A test technique has been developed for simulating the installation of suction piles in sand or clay. Piles with a diameter of 10 metres and a height of 9 metres can be simulated. In order to simulate the influence of the water depth on the installation pressure, the test is carried out in a pressure vessel. During a test the pressure difference is monitored. The penetration of the pile and water flow was measured by analyzing the video images. The data measured during a test is shown in Fig.10. The tests have shown that the driving force was proportional to the geometrical dimensions of the pile.

5.6 *Photoelastic stress measurement*

A missing element in experimental geotechnics is that the stresses cannot be measured in the interior of a sample of granular material. The only available method of obtaining continuous information about the stress distribution is the use of optically sensitive granular material, such as glass. An assembly of crushed glass can be made transparent by submerging the pores with a liquid with a matching refractive index. By means of polarized light, the stresses, for example, during a cone penetration test can be made visible. A first attempt to apply this test technique in a centrifuge is shown in Fig.11, where the stress underneath a footing before and after sliding is made visible.

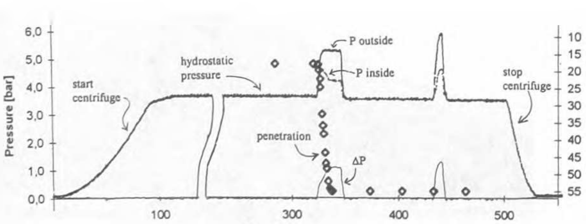

Fig.10 Measured data during installation of a suction pile.

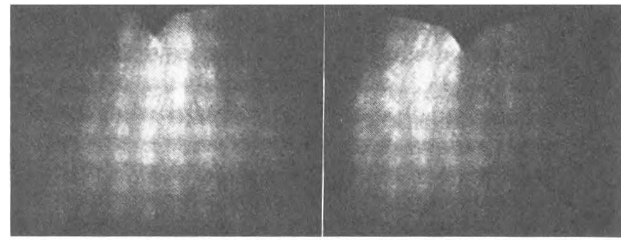

Fig.11 Centrifuge test with a footing using photoelastic granular material.

6 CONCLUSIONS

The small geotechnical centrifuge at the University of Delft has proved to be very successful in operation. The small size of the samples means that the machine is very flexible in operation and tests can be performed in a short period after an idea has been formulated.
Due to the application of state-of-the-art electronics, measuring techniques and special tools, advanced tests can be performed in flight. Since the computer is located in the spinning part of the centrifuge, only a few slip rings are required to manipulate on board equipment, and the electrical disturbances are minimal. The disadvantage of a small centrifuge -limited space for sensors- could be neutralized partly by using image processing techniques. Several different types of tests can also be performed in the small centrifuge. It appears that the small samples could be reproduced accurately with the automated device. In flight consolidation of slurry is the only way to produce a normally consolidated (soft) clay layer. Since the consolidation takes much time it is convenient to have a special centrifuge for this process.

ACKNOWLEDGEMENT

The centrifuges, electronics, soil preparation devices and testing equipment were all designed by the Geotechnical Laboratory of the Department of Civil Engineering at the University of Delft. Many thanks are given to several graduate students and the technicians of the laboratory, Mr. J. van Leeuwen, Mr. A. Mensinga and Mr. J.J. de Visser for their contributions to this research. Several research projects are supported by Shell International Exploration and Production (SIEP) and the Dutch Ministry of Transport and Public Works.

REFERENCES

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.* National Academy Press, Washington D.C., pp. 99-105.

Allersma, H.G.B., I.A.G. Ligtenberg, 1994c: Simulation of failure of dikes by water infiltration by waves. *Proc. Int. Conf. Centrifuge94*, Singapore, Balkema Rotterdam, pp. 289-294.

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

Allersma, H.G.B., L. Ravenswaay, E. Vos 1994e, Investigation of road widening on soft soils using a small centrifuge. Transportation Research Record No. 1462. National Academy Press, Washington D.C., pp.47-53.

Allersma,, H.G.B., H.G. Stuit, P. Holscher, 1994f: 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., B. Hospers, M.G. den Braber, 1996: Centrifuge tests on the sliding behaviour of spudcans. *49th Canadian Geotechnical Conference of the Canadian Geotechnical Society*, St, John's, New Foundland, pp. 199-206.

Leung, C.F., F.H. Lee, E.T.S. Tan 1994: Centrifuge94 *Proc. of the Int. Conf. Centrifuge94*, Singapore, Balkema, Rotterdam, 1991.