APPLICATION OF SMALL BEAM CENTRIFUGE IN GEOTECHNICAL RESEARCH

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ABSTRACT

Geotechnical centrifuges are used worldwide to investigate structures whose behaviour is strongly dependent on the mechanical properties of soil. Although centrifuge research is cheaper than real scale testing it is still expensive. The costs can be reduced significantly if the tests are performed in a small centrifuge. Using miniature equipment and advanced monitoring systems, many geotechnical problems can also be modeled in a small centrifuge. The preparation of a test takes relatively little time, so that the time interval between idea and results is short. An additional advantage is that small soil samples can be reproduced very accurately, so that slight modifications of the test models can be visualized.
A beam centrifuge with a diameter of two metres has been developed at the University of Delft. The design concept was to keep the device as simple as possible and to keep the weight of the samples so low that they could be carried by one person. To enable the performance of a large variety of tests, several miniature devices were developed, such as: a sand sprinkler, a two dimensional loading system, an air supply system, a water supply system and a vane apparatus. The limitation of space for sensors was neutralized by using image processing techniques to measure the deformation of the soil in flight.
Several research projects have been conducted, e.g.: sliding behaviour of spudcans, stability of dikes during wave overtopping, blowouts, stability of embankments during widening ,shear band analysis, buckling behaviour large diameter piles, suction pile installation, etc..

INTRODUCTION

Centrifuge research is helpful in investigating the behaviour of soil and other granular materials. For example, consider the behaviour of a vertical cut in clay. It is well known that at some depth failure of the cut occurs. It is not possible to investigate the stability of this problem in a small scale model at 1g condition, because the shear stresses are so low with respect to the cohesion that failure will never occur. In a centrifuge, however, the body force can be increased in an artificial way, so that even in a small model the same shear stresses can be realized as in the prototype problem. With this technique it is possible to use small scale models to visualize the behaviour of large size 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 wet sand the results are strongly dependent on the capillary pressure because the cohesion caused by this pressure is of the same magnitude as the interparticle stresses. In several practical problems the simulation of the stress dependent behaviour is of importance in order to make reliable predictions.
The late sixties can be considered as the beginning of a new era for centrifuge modeling. Several centrifuges were built for geotechnical work and a great variety of problems were studied by this technique (1). The tendency was to increase the size of the devices, so that the costs of tests became very high. For several geotechnical problems, however, the use of a small centrifuge is quite adequate.

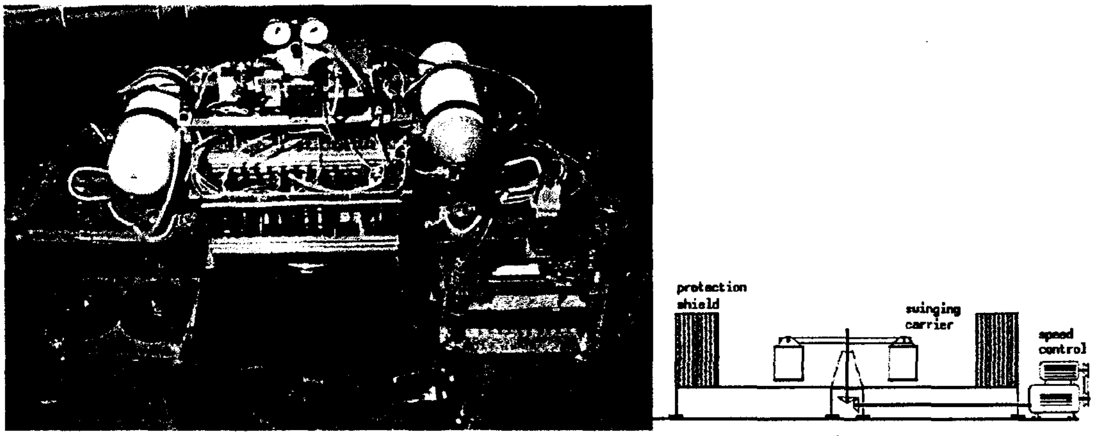

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Fig1 a) Photograph of the small centrifuge of the University of Delft. b) Schematic drawing.

By making an optimal choice between size and facilities and using up-to-date electronics and computer control effective tests can also be performed in a small centrifuge.
In 1988 the development of a small geotechnical beam centrifuge with a diameter of two metres was started at the Geotechnical Laboratory of the University of Delft. The device was operational in 1990. Test devices with a dimension of 300x400x450 mm and a weight of 300 N can be accelerated up to 300 g.
A small geotechnical centrifuge is relatively cheap to operate, and the development of the equipment did not take so long compared to a big centrifuge. To enable the performance of advanced tests in flight, the carriers of the centrifuge were made large enough to contain computer-controlled devices. Because the costs of operation are low, the device is suitable to perform trial and error tests. Modification of the centrifuge for different tests is simple, so that a flexible operation is obtained. 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. This is important if the results of similar tests have to be compared.
A disadvantage of a small centrifuge is the limitation in the use of sensors during a test. This restriction, however, can be compensated partly by using image processing techniques in video 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 supply of sand, water and air. The devices operate under software control, which runs in a single board PC compatible computer located in the spinning part of the centrifuge. The signals from load cells, pressure transducers and other sensors are received by the on-board computer without interference of slip rings. The computer is assessable in a normal way via slip rings and commercial available line drivers. The test devices are driven by small DC motors, which are manipulated by the on board computer.
Several devices have been developed to prepare sand and clay samples. 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 different research projects were conducted in the centrifuge, i.e.: sliding behaviour of spudcan foundations, stability of dikes during wave overtopping, gas blowouts and cratering, stability of embankments during widening, shear band analysis, buckling behaviour large diameter piles, simulation suction pile installation, pile driving, pollution transport, etc. Several project were carried out as a 6 month graduate study. In recent years the centrifuge was in operation almost every day, hence the flexibility is demonstrated by the fact that three quite different model tests were performed on some days.

THE SMALL GEOTECHNICAL CENTRIFUGE OF THE UNIVERSITY OF DELFT

Mechanical part

The geotechnical centrifuge at the University of Delft was designed by the Geotechnical Laboratory of the Department of Civil Engineering and was built by the mechanical workshop of the University.

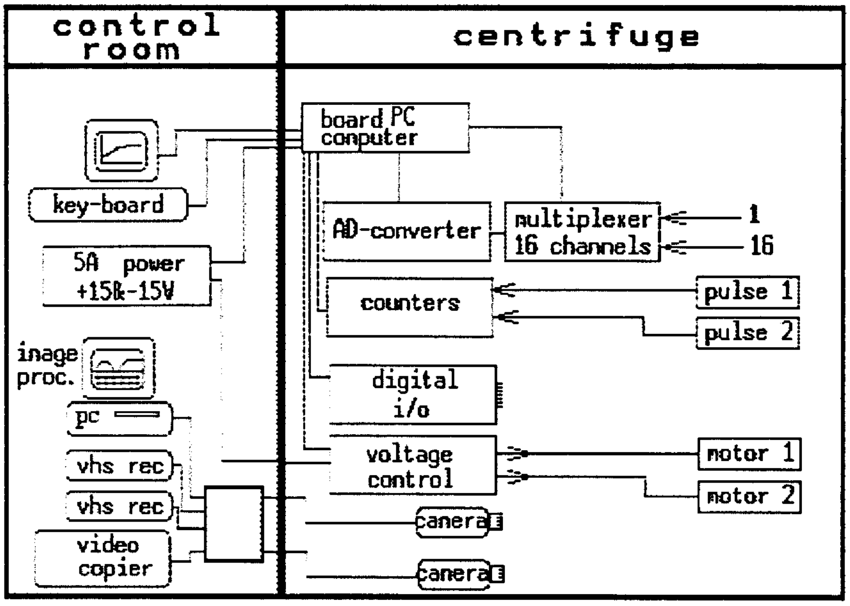

Fig.2 Diagram of the electronic control and measuring system.

The electronic systems were designed and built by the Geotechnical Laboratory. The advantage of the in-house design is that the system can be expanded and modified under internal supervision, which guarantees a good interaction between the facilities of the device and the tests. 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 450 mm apart, which are connected to each other by four cylindrical steel beams. The surface of the plates is 400 x 300 mm . Because the weight of the beam and carriers is large imbalance, which can occur during tests, has not a significant effect on the stability of the centrifuge. The potential danger from the spinning part of the centrifuge is minimized by a protection shield of steel (thickness= 5 mm) that forms a large cylindrical box. A second shield, 50 cm outside the first, is made of wooden plates. The gap between the two shields is filled with concrete blocks and granular material. This fill gives additional safety against flying projectiles and the weight stabilizes the device.
The centrifuge is driven by an electric motor of 18 kW via a hydraulic speed control unit. The hydraulic speed controller is manipulated by a step motor, which is interfaced to the speed control computer. 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 other test parameters, such as the pore water pressure in a clay sample.

Measuring facilities
The system electronics enables the performance of computer-controlled tests in flight (Fig.2). To minimize the number of slip rings the control system is placed in the spinning part of the centrifuge. The control unit contains a small single board computer (180x120x25mm ; 486CPU; 66MHz; 16Mbyte RAM; 32Mbyte solid state 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 input/output channels. For additional data storage a 1Gbyte hard disk unis is placed just in the center of the centrifuge. The signals from the sensors are conditioned by on-board amplifiers. 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 PC in the control room. By means of commercial available line driver units is was possible to realize a normal access to the board computer.

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

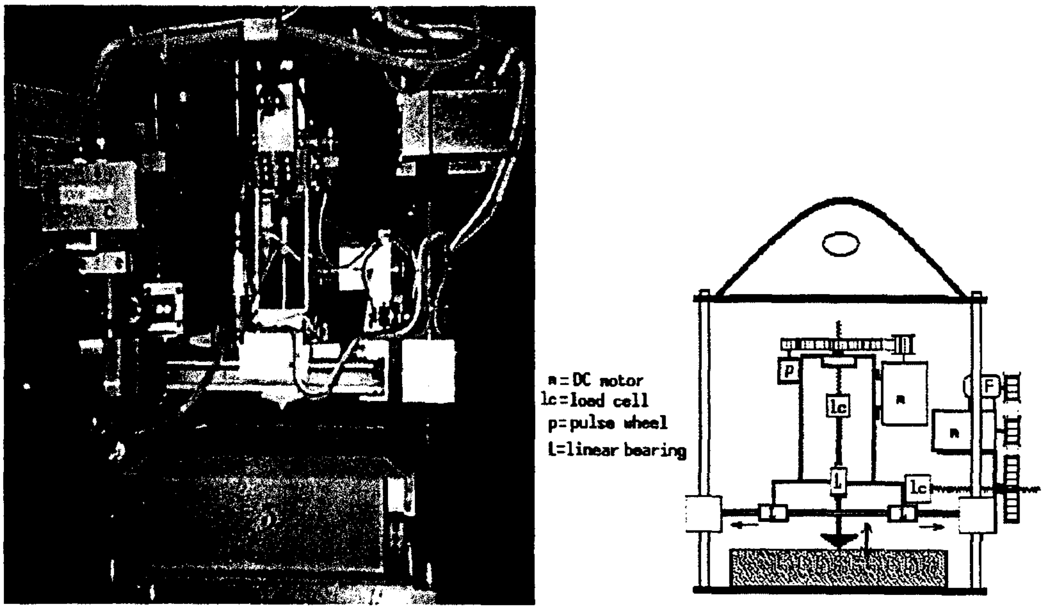

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Fig.3 a) Photograph of the two dimensional loading device, mounted in the centrifuge. b) Schematic drawing of the loading device.

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 (2). This technique has proven to be very useful in several research projects.

THE TEST EQUIPMENT

Several devices have been developed by the Geotechnical Laboratory of the University of Delft to perform tests in flight. The mechanical equipment, electronic system and control software are designed in all details by the laboratory. The following devices are available:

- Two dimensional loading system
- Sand sprinkler
- Vane apparatus
- Gas supply system
- Water supply system
- Pile driving unit
- Suction pile simulator

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. Two guiding systems based on linear ball bearings and axes of tempered steel guarantee a low friction translation in two perpendicular directions. The system is driven by two miniature DC motors. The translation is achieved by means of a screw spindle with a translation of 1 mm per revolution. The number of revolutions is counted by means of small pulse generators, which also detect the direction of rotation. One revolution is equivalent to 200 pulses. A special interface has been built to make it possible for the pulses to be used in the control program in order to determine displacements in the two perpendicular directions. The loads in the two perpendicular directions are measured by means of load cells. The outputs of the load cells are multiplied and can be used in a computer program via the multiplexer and the analog-to-digital-converter. Sufficient information is available to perform load or displacement controlled tests.

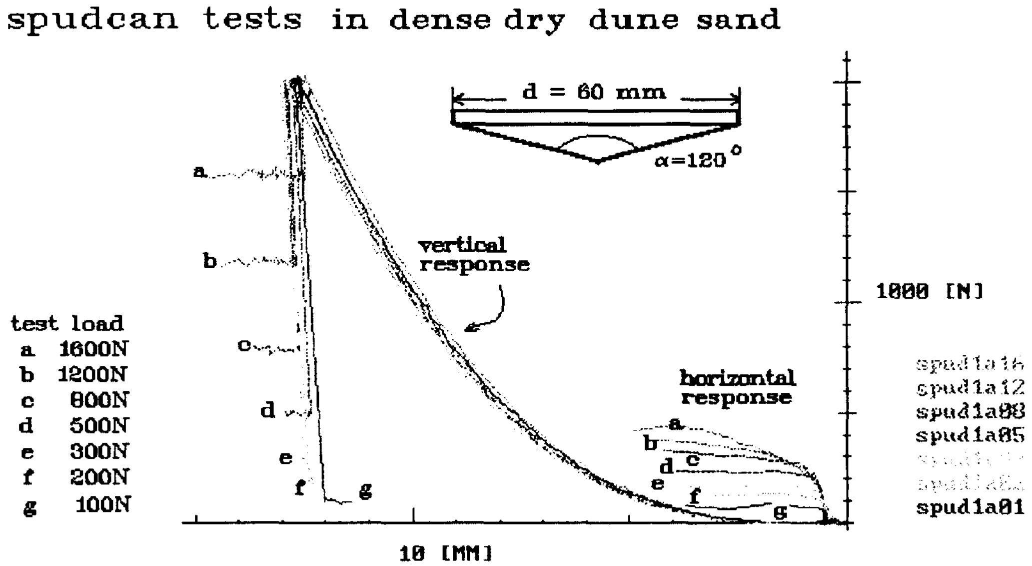

Fig.4 Typical output of a sliding test of a spudcan on sand

Furthermore the device can be used as a simple robot to manipulate a test during flight. Loads of more than 5 kN can be applied by the system. The accuracy of the measurement of the displacement (determined at 100g by image processing) is better that 0.1 mm, where the maximum displacement is about 50 mm. Up to now the device has been used at gravitation levels of more than 150 g. The weight of the two dimensional loading device is approximately 10 kg. It takes about ten minutes to install the loading system in the centrifuge. As an example, the typical output of a test with a spudcan foundation on sand is shown in Fig.4. In this test series the sliding resistance of the foundation element at different vertical loads is investigated, in order to make predictions about the behaviour of offshore platforms during heavy storms. Spudcans with a diameter of more than 14 metres can be simulated. Other tests that can be performed are, for example: anchors, bulldozer, footing, excavation (3).

Sand sprinkler

A computer controlled sand sprinkler has been developed to make embankments in flight. The device consists of a hopper, which can be translated easily by means of linear ball bearings and axes of tempered steel (Fig. 5a). The weight of the device is approximately 10 kg. The translation (range is 150 mm) is realized by means of a small DC motor. The position of the hopper is detected by means of a pulse wheel and a 16 bit counter, which can be accessed in the program of the control computer. The sprinkler system is designed in such a way that no close seals are required. An axis is located in the outlet of the hopper in such a way that the granular material flows only when the axis is rotated. This mechanism has proven to be reliable up to 120g. The axis of the sprinkler system is also driven by a small DC motor and the amount of deposited sand is detected by counting the number of revolutions by means of a pulse wheel. Several options can be assessed in the control program. It is possible to sprinkle sand layer by layer or at one particular location. The disturbing effect of the Coriolis forces is minimized by means of hinged sheets, which guide the sand grains. On the other hand the Coriolis effect can be used to build an embankment with a gradient in height over the width of the sample box. This can be used to investigate time effects in the failure of clay under embankments. Optionally, the control program of the sand sprinkler also reads the output of pressure transducers, which can be placed in the clay layer. The pore water pressure is plotted on the screen. An automatic link can be made between the pore water pressure and the sand supply scheme. The creation of a dike during sand supply and the deformation of the clay can be monitored by a video camera. The deformation of the clay is made visible by means of a grid.

Software has been developed by the laboratory (2) to digitize the coordinates of the nodes of the grid automatically by means of image processing. In principle it is possible to make an automatic link between the sand supply program and the image processing system. so that an embankment can be built in flight where the images of the video camera are used to control the sand supply. The sand sprinkler system is used to

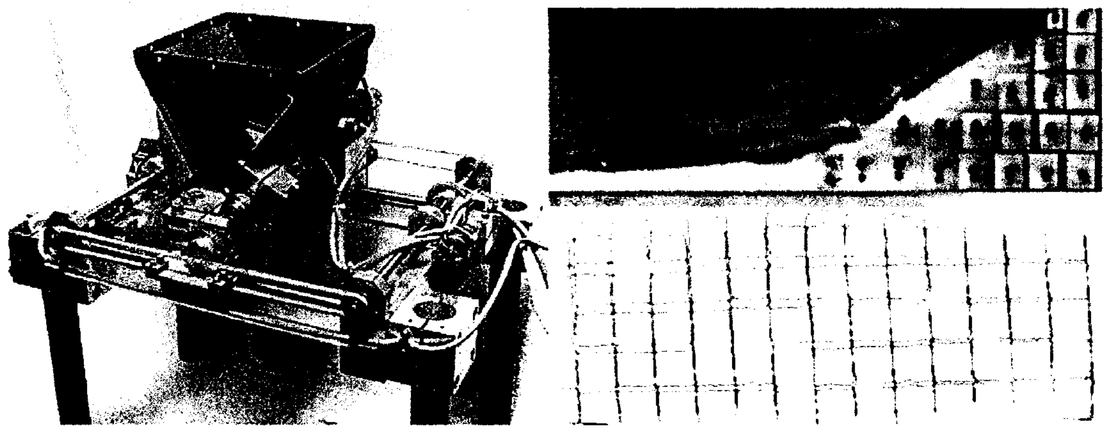

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Fig.5 a) Photograph of the sand sprinkler system. b) Deformation under an embankment on clay.

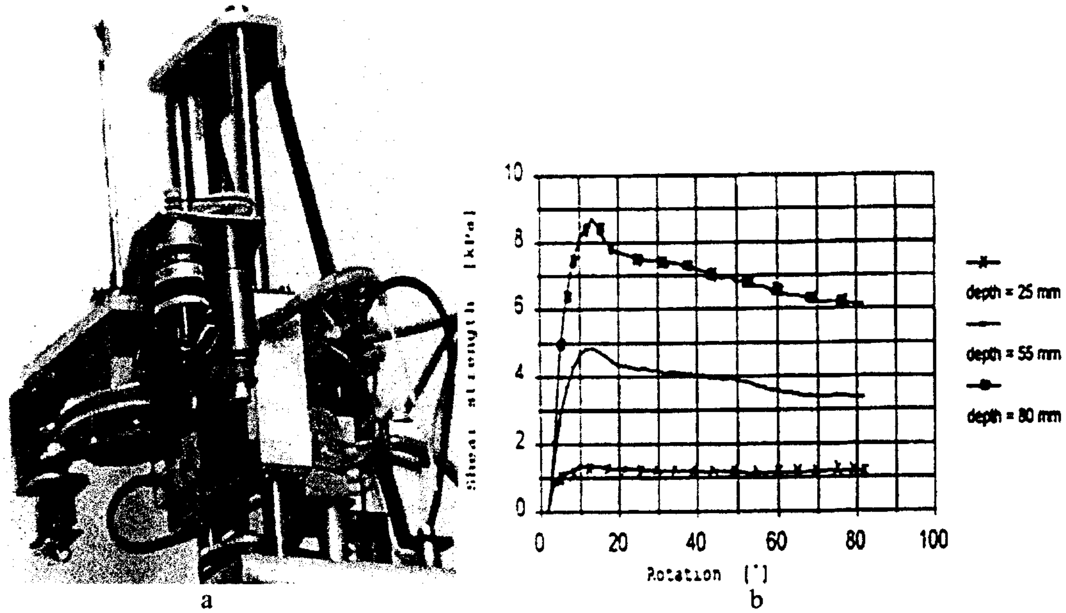

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Fig.6 a) Photograph of the miniature vane apparatus. b) Typical output of a vane tests.

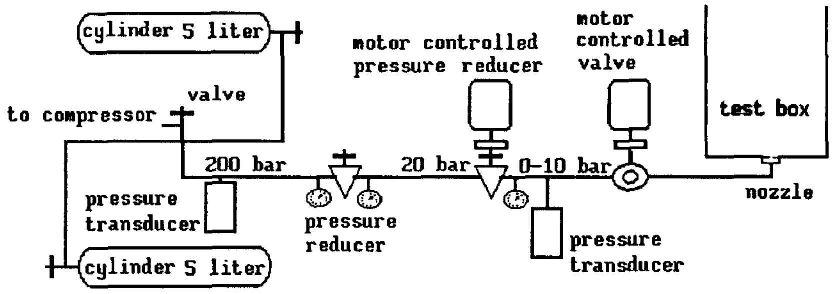

Fig.7 Diagram of the air supply system.

investigate the stability of dikes and different methods of widening of embankments, which are founded on soft soils (Fig.5b). Since the centrifuge has two swinging platforms, the loading system and the sand sprinkler can both be mounted in the centrifuge. In this way the centrifuge can be used efficiently.

Vane apparatus

To correlate the test results with calculation methods, information is required about the properties of the soil types used. In the case of clay how the undrained shear strength changes with the depth during the test must be known. Information about the shear strength can be obtained by means of a vane apparatus (Fig.6). In this technique a shaft with four blades is pushed into the clay sample. The shaft is then rotated and the torque required to rotate the vane in the clay is measured and recorded. The typical course of the torque during rotation of the vane is shown in Fig.6 also. The undrained shear strength is calculated from the maximum torque and the surface area of the cylindrical soil unit which is rotated by the vane. It appeared that the measured values are dependent on several factors. Therefore the vane apparatus has been automated in such a way that the depth (range 100 mm) and penetration speed can be adjusted in flight.

The time between penetration and rotation, and the rotation speed of the vane can also be varied. The position of the vane can be adjusted over a range of 250 mm during flight, so that several tests can be performed without stopping the centrifuge. Three miniature DC motors are used to control the device. A special sensor has been developed to measure the torque. The weight of the vane apparatus is approximately 3 kg and the outside dimensions are 180x150x200mm .

Gas supply system

In some tests gas supply to a soil sample is required. 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 (Fig.1). Before a test is started the cylinders are filled with air by means of a high pressure compressor. A computer controlled air supply system has been developed in order to regulate the gas flow from a distance. The system is shown schematically in Fig.7. The pressure of the supplied air is controlled by a conventional pressure regulator, which is modified in such a way that it can be driven by a small DC motor. The output pressure of the regulator is detected by a pressure transducer and used in the computer program to control the DC motor. A modified valve, which is also driven by a small DC motor is used to start or stop the gas flow quickly. The gas flow per unit of time is measured by measuring the pressure drop of the gas cylinders during the test. A computer program has been developed to interactively control the gas supply. During a test the cylinder pressure, the test pressure and the gas flow are plotted on the screen. Flow rates of 10 l/s can be reached. The gas in the high pressure cylinders represents a lot of power, which can be used, in principle, for tests in which large loads or energy are needed.

The gas supply system is used to simulate blowouts and cratering (Fig.8) in a sand layer with an equivalent thickness of approximately 20 - 30 metres.

Water supply system
In several geotechnical problems it is required to control water flow in the spinning centrifuge. It is not so easy to control the water supply because rather high pressures (and energy) are required to overcome the acceleration. At this moment two systems are available. In the most simple system the water is circulated by means of an air jet (Fig.9). The air supply system is used to control the jet. The advantage of this system is that the water supply can be controlled smoothly from zero to maximum flow. The flow rate can be measured by means of a small turbine. A maximum flow of about 10 l/min can be obtained. The second system uses a small pump, which is commercially available as an accessory for electric drilling machines. In the centrifuge there is not enough electric power available to drive such a pump. Therefore an air motor has been applied. An air motor delivers a lot of power per unit of weight and uses the air more efficiently than an air jet. The air motor has proven to be reliable up to at least 130g. An additional advantage of an air motor is that no electric power drop can hang up the control computer. The speed of the air motor cannot be controlled smoothly from zero, so that a large water flow is generated at start up. The water flow rate is measured by means of a small turbine.
The water circulation system is used to investigate the stability of dikes during water infiltration, which can occur by wave overtopping. In Fig.9 it is visualized in two stages how a sand slope, which

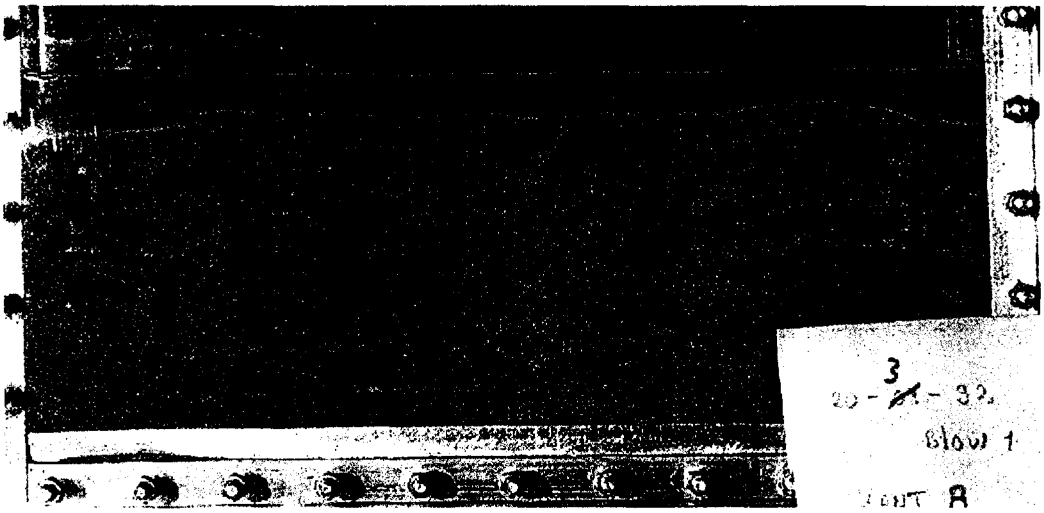

Fig.8 Photograph of the simulation of cratering in a sand layer with a height of 20m.

was covered with a thin clay layer, collapses. The most dark area shows sand which is saturated with water.

Pile driving unit
A simple pile driving unit has been developed to install piles during flight. A diagram of the device is shown in Fig.10a. A cylinder contains a piston, which is lifted up by supplying air shots. After the air has been escaped the piston is falling down. Sufficient impact is obtained to drive piles into sand samples. Since the device would not be very stable if the air is supplied by a flexible tube, a telescope is used to connect the pile driving unit with the air circuit. The telescope stabilizes the driving unit and allows vertical displacement of the device with a minimum of change in the mechanical properties.
Up to now the pile driving unit is mainly used to examine the buckling behaviour of large diameter piles during driving in sand. Pile driving was required in order to prevent plugging of the soil. It was found that buckling (Fig10b) occurs only if the tip of the pile was damaged slightly.
The pile driving unit can operate in combination with the loading system, so that it is possible to perform a test load after driving, without stopping the centrifuge.

Suction pile simulator
Suction piles are used offshore as foundation elements or as anchors. Suction piles are attractive thanks to the convenient method of installation. A pile with a diameter of 9m and a height of 10m can be installed in 1 hour, by using a pump only. Although in general installation is not a problem, questions arises when

new applications have to be considered. Examples are the installation in layered soils and e.g. onshore applications. Mathematical analysis of this phenomenon is quite delicate, because the soil parameters are changing during installation. The large dimensions make real scale testing not very attractive. Therefore centrifuge tests seems to be the best way to examine this foundation technique. However, a problem arises how to simulate a small pump, and to model a realistic water depth. Both problems can be solved by performing the test in a container which can be pressurized. The test setup is shown in Fig. 11. A suction pile is placed on a sand bed. The inside of the suction can is connected via a measuring cylinder with the atmospheric pressure, where a water flow is generated by pressurizing the container. Pressure differences which belong to a water depht of more than 50 metres can be simulated. A typical digitized test result is shown in Fig. 12.

SAMPLE PREPARATION DEVICES

An important aspect of centrifuge research is sample preparation. To achieve good test results, the following is required:
- The ability to use samples of different soil types

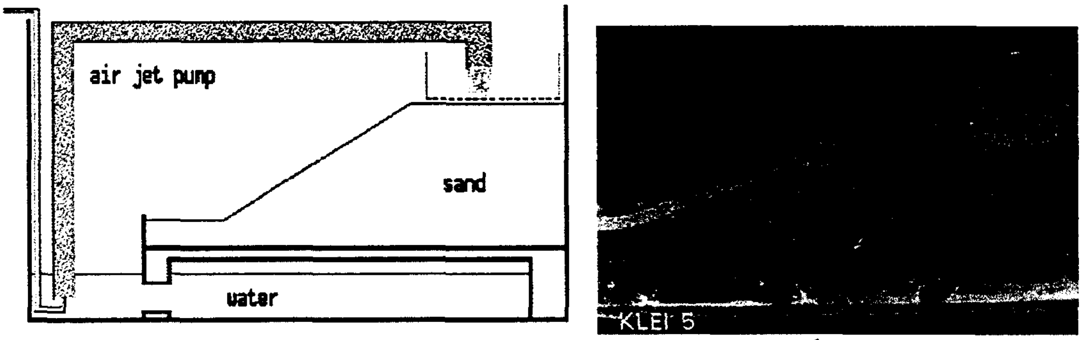

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Fig.9 a) Diagram of the air jet pump. b) Fialure of a sand slope, covered with clay, due to water infiltration at the crest.

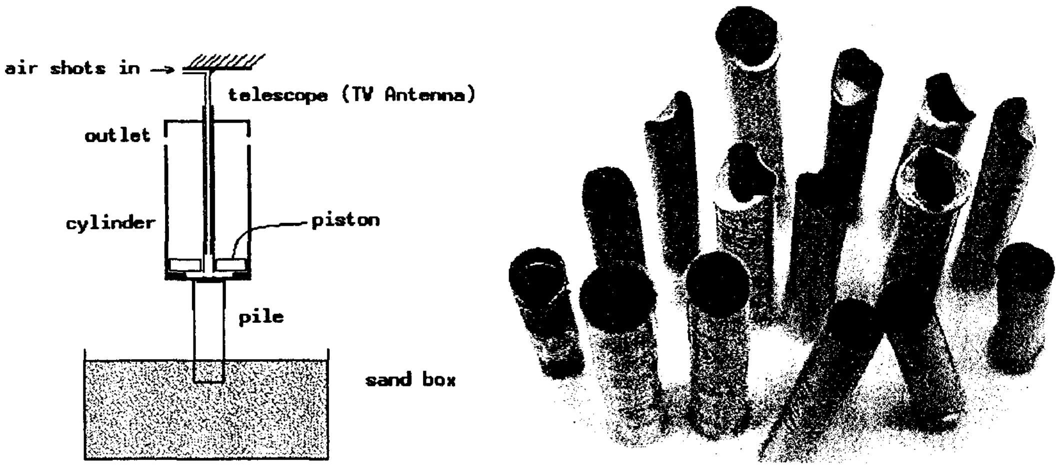

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Fig.10 a) Diagram pile driving unit. b) Example of tested piles.

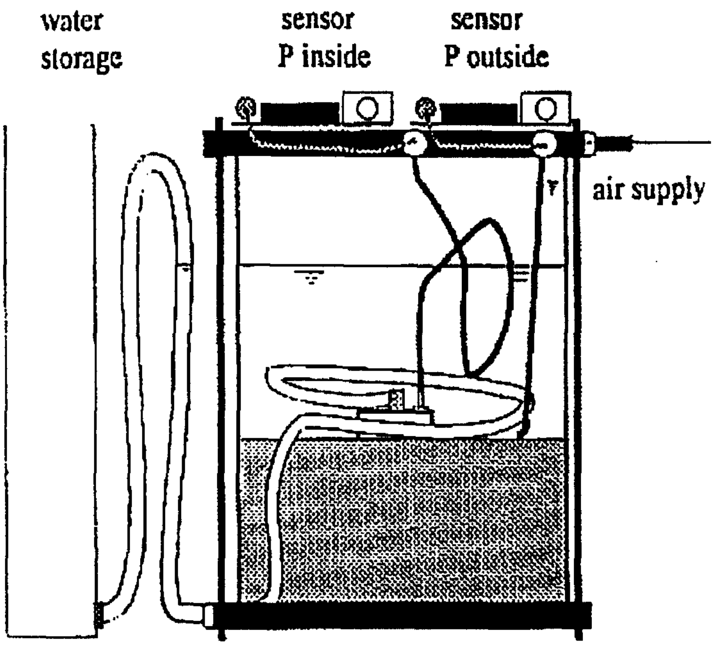

Fig.11 Diagram test setup to simulate suction pile installation.

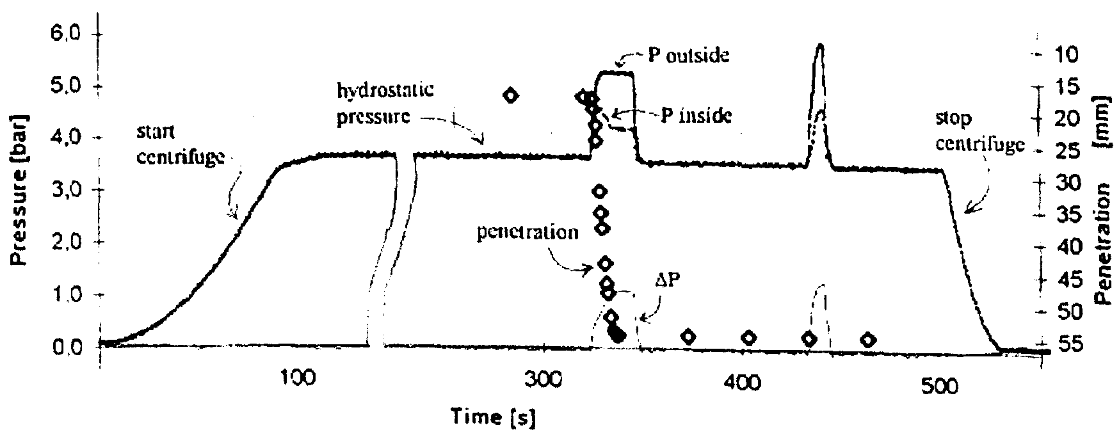

Fig.12 Typical dat measured during a test with a suction pile.

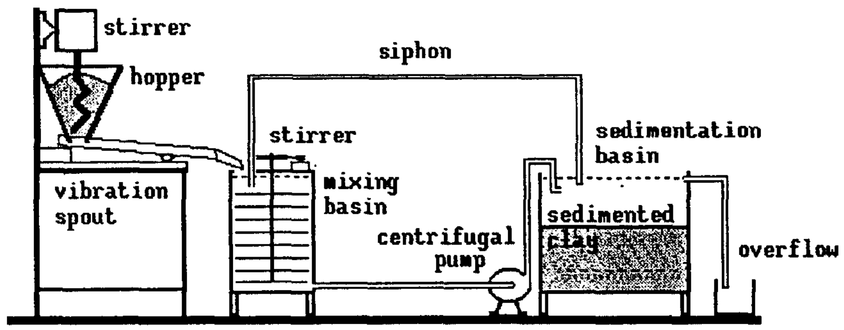

Fig. 13 Diagram of the clay mixing device.

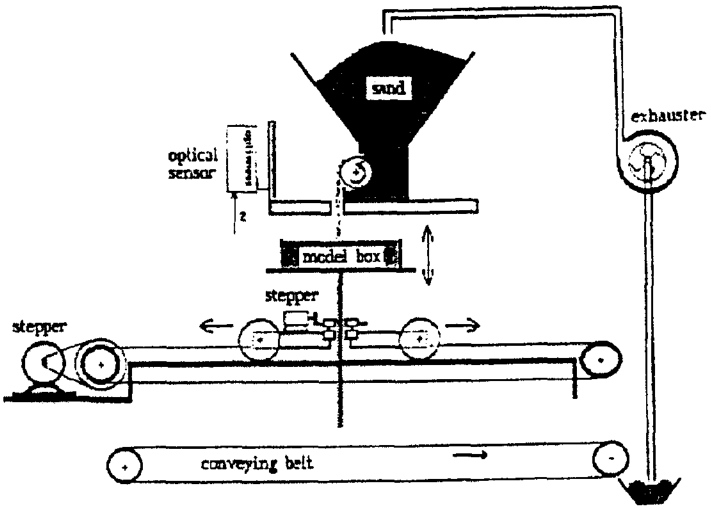

Fig. 14 Diagram of the sand preparation device

- The ability to vary sand densities
- The ability to accurately reproduce samples, so that results from different tests can be compared.

Two different devices have been developed in order to prepare clay or sand layers.

Clay preparation

Up to now it was found that the best control over the samples is obtained by making artificial clay. In this technique clay powder (several types are commercial available) 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 device operates more or less automatically and is self cleaning. The principle of the device is that the clay is added in a thin layer to a rotating water surface (Fig. 13), so that no air is included due to differences in capillarity. The water with a very low clay content is pumped to a basin where the clay is sedimented. The clay slurry, with a water content of approximately 100%, is homogenized in a mixer before it is put into the sample boxes. The best way to obtain a soft, normally consolidated soil with a smooth and realistic gradient of water content and strength over the height of the sample is to consolidate the slurry in the centrifuge at the same g level as will be used in the tests. The

consolidation will take several hours or even days when a low permeable clay is used. Because the centrifuge will be occupied all that time no other tests can be performed. Therefore a special centrifuge has been built which is only used to consolidate the clay layers. This centrifuge has a diameter of 1 metre and can accelerate sample boxes with a weight of approximately 200N up to 200g.
The consolidation can be followed by pressure transducers via slip rings. Or by means of a small camera. The settlement of the clay surface can be digitized in real time by using image processing.
To improve the reproducibility of the sample preparation a technique has been developed to copy a grid at the surface of a black or white clay without removing boundaries. A grid is plotted on a special sheet which is made waterproof by a thin cover. This sheet is placed in the sample box which is filled with slurry. After consolidation the protection cover is removed. Due to the water the grid is copied to the clay surface, were the special layer on the sheet became very smooth. A grid with a good contrast is required to derive the deformation of the clay by image processing.

Sand preparation machine
A computer controlled device has been developed to prepare well defined sand layers in the test containers (Fig.14). Since this device is completely automated, very good reproducible samples can be made. The sand, which is stored in a hopper can be sprinkled in a curtain by means of a rotating axis, following the same technique as the in flight sand sprinkler. The falling height of the sand can be adjusted. The distance to the sand surface is measured by means of an optical sensor and the height of the test box is adjusted by a step motor in order to keep the falling height constant during raining. The sample box is moved back and forth by means of a second step motor, while a smooth acceleration is realized in the turning points to prevent shocks. The sand supply system can be controlled in the computer program, so that only sand is sprinkled when the sample box is located under the outlet of the hopper. The wasted sand is transported by a belt to a container. The sand level in the container is detected by a photo cell. Depending on the sand level, a vacuum cleaner is started, so that the wasted sand is transported back to the hopper. Special precautions are taken to prevent the fine material from being extracted from the sand used, because it was found that small changes in the composition has a large influence on the mechanical properties of the sand.
Sand samples with a surface of 300x300 mm and a maximum thickness of approximately 150 mm can be made. The porosity, depending on the sand type, can be varied between 35% and 39%. The porosity of the sand layers can be reproduced with an accuracy of less than one percent. The preparation of the sample with a thickness of 100mm takes about 20 minutes.

CONCLUSIONS

The small geotechnical centrifuge at the University of Delft has provided successful operation. The small size of the samples means that the machine is very flexible in operation and that tests can be performed in a short time 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 control computer is located in the spinning part of the centrifuge, only a few slip rings are required to interface the spinning equipment with the PC in the control room. The disadvantage of a small centrifuge -limited space for sensors- is partly overcome by using image processing techniques. A video camera is used to monitor the sample, getting displacements from the video image. Several different types of tests can be performed in the small centrifuge and several different type of tests can be performed on the same day. Much attention has been paid to techniques to prepare reproducible samples. Reproducible sand samples can be prepared with the automated sand sprinkler device. In flight consolidation of the slurry is the only way to produce normally consolidated (soft) clay layer. A special centrifuge, built to consolidate clay samples, has increased the capacity of the main centrifuge.

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