Development of Miniature Equipment for a Small Geotechnical Centrifuge

H. G. B. ALLERSMA

Geotechnical centrifuges are used worldwide to investigate structures whose behaviors are 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. By 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 the idea and the results is short. An additional advantage is that tests with small soil samples can be reproduced very accurately, so that slight modifications of the test models can be visualized. A centrifuge with a diameter of 2 m 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 in the centrifuge, for example, shear band analysis and investigations of the sliding behaviors of spudcan foundations, the stabilities of dikes during wave overtopping, blowouts, and the stabilities of embankments during widening.

Centrifuge research is helpful in investigating the behaviors of soil and other granular materials. For example, consider the behavior 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 the 1-*g* 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 that occur in the prototype can be realized. With this technique it is possible to use small-scale models to visualize the behaviors of large-size problems. Clay is a typical example of a material with a strong stress-dependent behavior, but materials like sand also 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 behavior is of importance for making reliable predictions.

Faculty of Civil Engineering, Delft University of Technology, Stevinweg 1, 2628CN Delft, The Netherlands.

The late 1960s can be considered the beginning of a new era for centrifuge modeling. Several centrifuges were built for geotechnical work, and a wide variety of problems were studied by this technique (*1*). The tendency was to increase the size of the devices, so that the costs of the tests became very high. For several geotechnical problems, however, the use of a small centrifuge is adequate. 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 centrifuge with a diameter of 2 m was started at the Geotechnical Laboratory of the University of Delft. The device was operational in 1990. A test device with dimensions of 300 × 400 × 450 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 as long as it did for a large 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 for use in performing 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 tests 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 must be compared. A disadvantage of a small centrifuge is the limitation in the sensors that can be used during a test. This restriction, however, can be compensated for partly by using image processing techniques of video images taken with the onboard video camera.

Miniature devices have been developed for performing advanced tests in flight, such as loading, displacing, and controlling the supply of sand, water, and air. The devices operate under software control, which runs in a small computer located in the spinning part of the centrifuge. The signals from load cells, pressure transducers, and other sensors are received by the onboard computer without interference from the slip rings. Information is exchanged with the outside world via slip rings by using the RS232 protocol. The test devices are driven by small direct current motors, which are manipulated by the onboard 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 to obtain a very soft normally consolidated clay.

In 1993, five different research projects were conducted in the centrifuge: shear band analysis and investigations of the sliding behaviors of spudcan foundations, the stabilities of dikes during wave overtopping, blowouts and cratering, and the stabilities of embankments during widening. Each project was carried out as a 6-month study. The centrifuge was in operation almost every day; hence, the flexibility is demonstrated by the fact that tests with three very different models were performed on some days.

SMALL GEOTECHNICAL CENTRIFUGE OF THE UNIVERSITY OF DELFT

Mechanical Parts

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. 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.

The centrifuge frame is fixed to the floor and bears the vertical axis and the protection shield (Figure 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 separated by 450 mm and connected to each other by four cylindrical steel beams. The surface of each plate is 400 × 300 mm. Because the weight of the beam and carriers is large, imbalance, which can occur during tests, has not had a significant effect on the stability of the centrifuge.

The potential danger from the spinning part of the centrifuge is minimized by a steel protection shield (thickness = 5 mm) that forms a large cylindrical box. A second shield located 50 cm outside of the first one 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 objects, and the weight stabilizes the device.

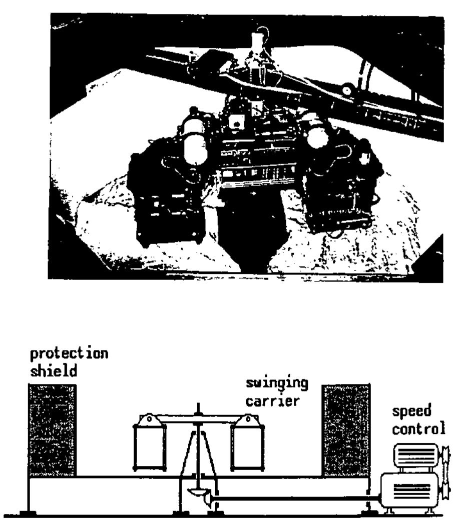

FIGURE 1 Small centrifuge of the University of Delft: *top*, photograph; *bottom*, schematic drawing.

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 the speed control computer. A computer program has been developed to adjust the speed of the centrifuge by using a tachometer signal. Several options are available for controlling the speed. It is possible, for example, 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's electronics enable the performance of computer-controlled tests in flight (Figure 2). To minimize the number of slip rings that are needed, the primary control units are placed in the spinning part of the centrifuge. The control unit contains a small single-board computer (180 × 120 × 25 mm, a 486 central processing unit, 66 MHz, 16-megabyte random-access memory, and 3 megabyte flash read-only memory), a 12-bit analog-to-digital (AD) converter with a 16-channel multiplexer, two voltage-controlled outputs of 8 A each, and two 16-bit counters. The signals from the sensors are conditioned by amplifiers. Eight power slip rings are available to feed the electronics and the actuators. Twelve high-quality slip rings are used to transmit the more sensitive signals, for example, two video lines and the RS232 connection between the onboard computer and the personal computer (PC) in the control room. During a test the relevant parameters are sent to the PC in the control room. There the data are displayed in graphic form and are stored on a hard disk.

A special feature is that several phenomena can be measured by using the video images. By 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 (*2–4*). This technique has proven to be very useful in several research projects.

TEST EQUIPMENT

Several devices have been developed by the Geotechnical Laboratory of the University of Delft for use in performing tests in flight. All details of the mechanical equipment, the electronic sys-

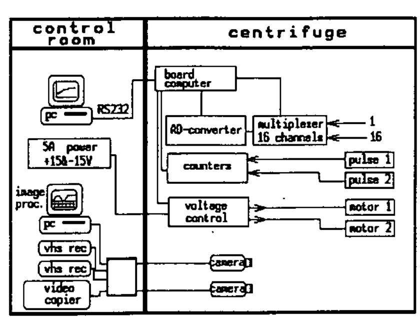

FIGURE 2 Electronic control and measuring system.

tem, and control software are designed by the laboratory. The following devices are available:

- Two-dimensional loading system,
- Sand sprinkler,
- Vane apparatus,
- Gas supply system, and
- Water supply system.

Two-Dimensional Loading System

The two-dimensional loading system (Figure 3) can be considered a universal tool that 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/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 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 so that load- or displacement-controlled tests can be performed. 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 by 100 *g* by image processing) is greater than 0.1 mm, and 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 10 min 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 Figure 4. In this test series the sliding resistance of the foundation element at different vertical loads is investigated to make predictions about the behavior of offshore platforms during heavy storms. Spudcans with diameters of more than 14 m can be simulated. Tests with other systems can be performed, for example, anchors, bulldozers, footings, and excavations (*3*).

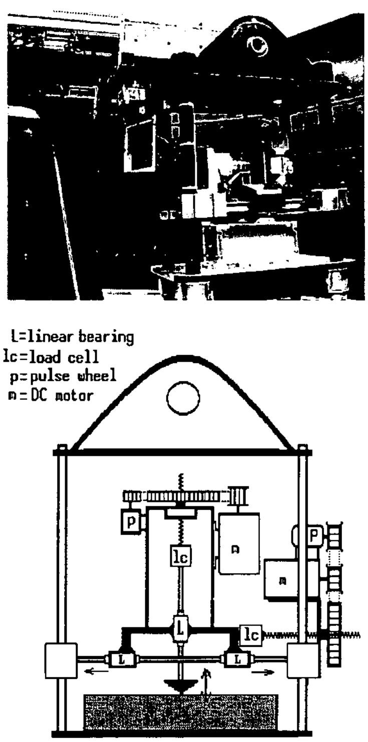

FIGURE 3 Two-dimensional loading device mounted in the centrifuge: *top*, photograph; *bottom*, schematic drawing.

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 (Figure 5). 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 120 *g*.

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 force 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 em-

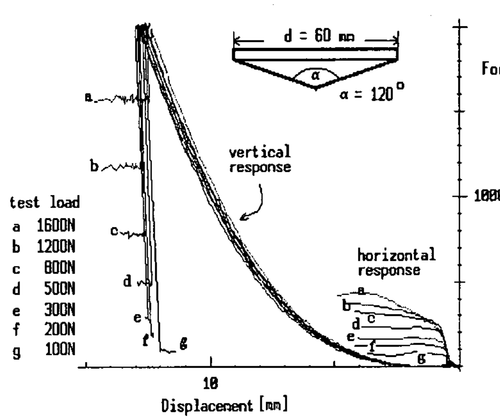

FIGURE 4 Typical output of a sliding test of a spudcan footing on sand.

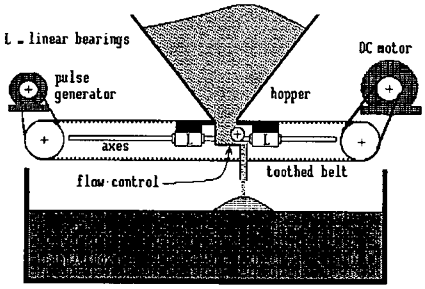

FIGURE 5 Sand sprinkler system.

bankments. Optionally, the control program of the sand sprinkler also reads the outputs 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; the images provided by the video camera are used to control the sand supply. The sand sprinkler system is used to investigate the stabilities of dikes and different methods of widening of embankments that are founded on soft soils. 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.

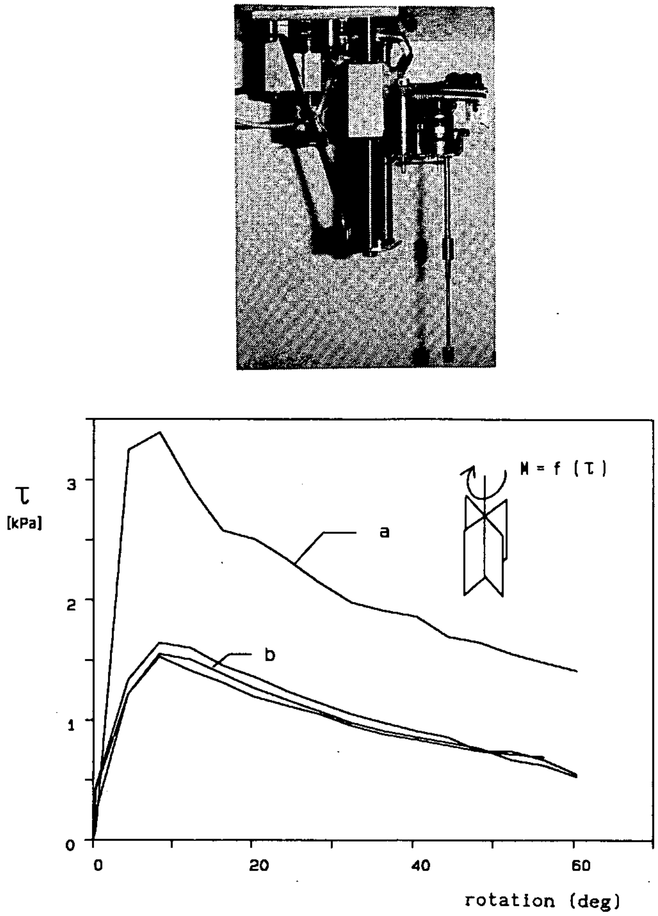

FIGURE 6 *Top*, miniature vane apparatus; *bottom*, typical output of a vane test.

Vane Apparatus

To correlate the test results with calculation methods, information about the properties of the soil types used is required. 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 (Figure 6). By 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 also shown in Figure 6. The undrained shear strength is calculated from the maximum torque and the surface area of the cylindrical soil unit that 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 the 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 180 × 150 × 200 mm.

Gas Supply System

In some tests a gas supply to a soil sample is required. Since the small centrifuge is not equipped with fluid slip rings, the gas must 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 L each are mounted on the beam of the centrifuge (Figure 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 to regulate the gas flow from a distance. The system is shown schematically in Figure 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

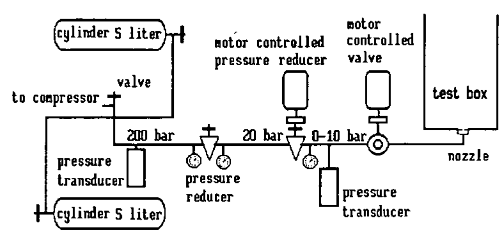

FIGURE 7 Air supply system.

driven by a small dc motor. The output pressure of the regulator is detected by a pressure transducer and is 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 in 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/sec 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 amounts of energy are needed.

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

Water Supply System

In several geotechnical problems it is required to control water flow in the spinning centrifuge. It is not easy to control the water supply in the centrifuge because rather high pressures (and large amounts of energy) are required to overcome the acceleration. At present two systems are available. In the simpler system the water is circulated by means of an air jet (Figure 9 *top*). 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 rate 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 130 *g*. 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. Figure 9, *bottom*, visualizes in two stages how a sand slope, which was covered with a thin clay layer, collapses. The darkest area shows sand that is saturated with water.

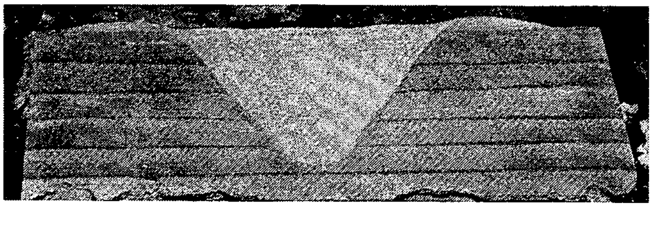

FIGURE 8 Simulation of cratering in a sand layer with a height of 20 m.

SAMPLE PREPARATION DEVICES

An important aspect of centrifuge research is sample preparation. To achieve good test results, the following are required:

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

Two different devices have been developed for use in the preparation of clay or sand layers.

Clay Preparation

Up to now it was found that the best way to control the samples is to make artificial clay. By this technique clay powder (several types are commercially available) is mixed with water, and the air content is kept as low as possible. A technique in which an air-free slurry is obtained under normal atmospheric pressure has been developed. 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 (Figure 10) so that no air is included because of differences in capillarities. 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 percent, 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 *g* level to be used in the tests. The consolidation will take several hours or even days when a clay with low permeability is used. Because 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. This centrifuge has a diameter of 1 m and can accelerate sample boxes with a weight of approximately 200 N up to 200 *g*. The consolidation can be followed by pressure transducers via slip rings.

To improve the reproducibility of the sample preparation, a technique of copying a grid on the surface of a black or a white clay without removing boundaries has been developed. A grid is plotted on a special sheet that is made waterproof by use of a thin cover. This sheet is placed in the sample box, which is filled with slurry. After consolidation the protective cover is removed. Because of the water, the grid is copied onto the clay surface, and the special layer on the sheet becomes 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 (Figure 11). Since this device is completely automated, very good, reproducible samples can be obtained. The sand, which is stored in a hopper, can be sprinkled in a curtain by means of a rotating axis by following the same technique used for the in-flight sand sprinkler. The falling height of the sand can be adjusted. The distance to the sand

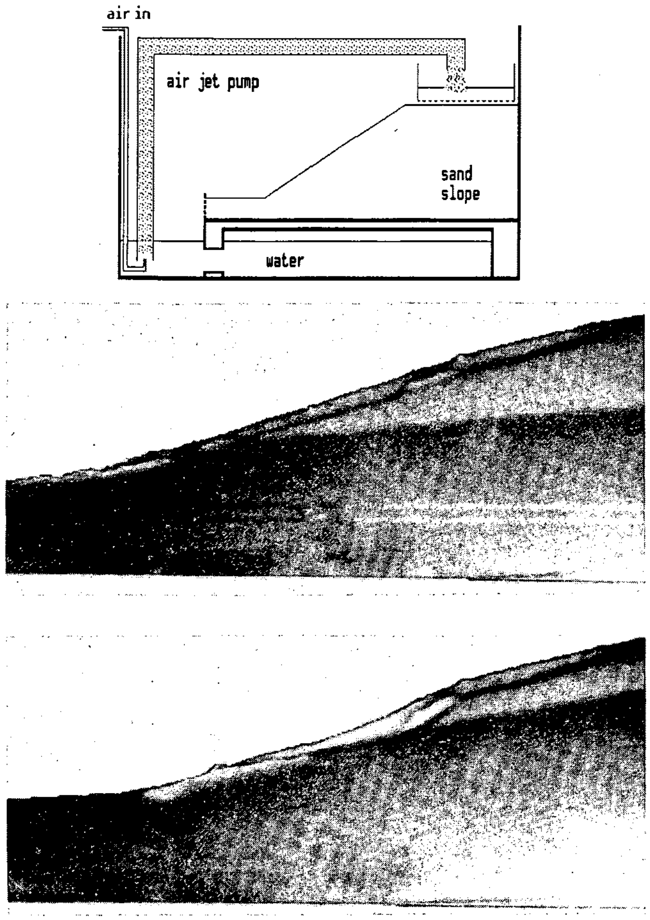

FIGURE 9 *Top,* air jet pump; *bottom,* failure of a sand slope covered with clay because of water infiltration at the crest.

surface is measured by means of an optical sensor, and the height of the test box is adjusted by a step motor to keep the falling height constant during raining of the sand. The sample box is moved back and forth by means of a second step motor, and a smooth acceleration in the turning points is used 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 have large influences on the mechanical properties of the sand.

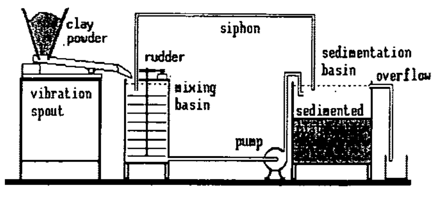

FIGURE 10 Clay-mixing device.

Sand samples with a surface of 300 × 300 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 percent. The porosity of the sand layers can be reproduced with an accuracy of less than 1 percent. The preparation of the sample with a thickness of 100 mm takes about 20 min.

CONCLUSIONS

The small geotechnical centrifuge at the University of Delft has proved to be successful in 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. Because of 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 types of tests can be performed on the same day.

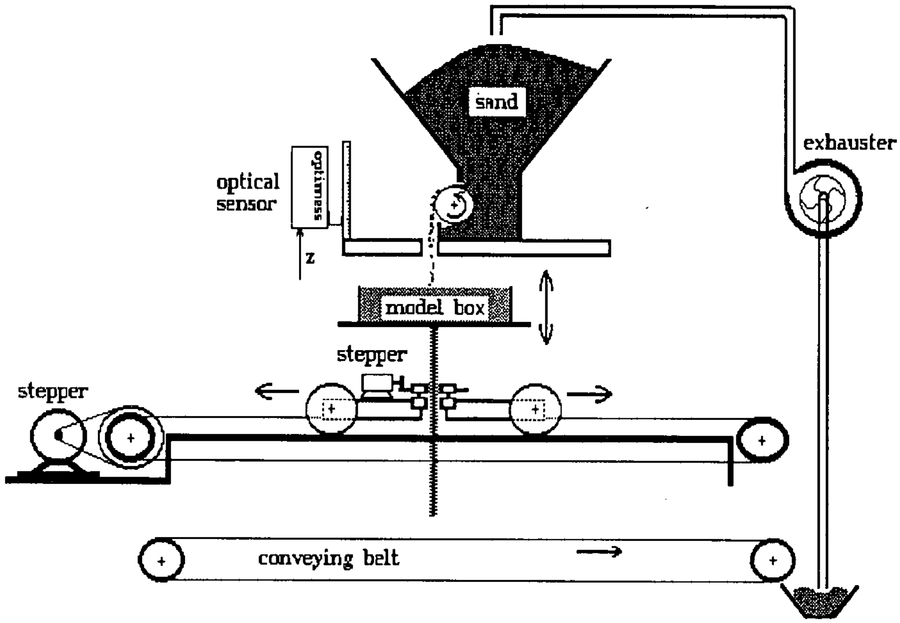

FIGURE 11 Sand preparation device.

Much attention has been paid to the techniques used 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 a normally consolidated (soft) clay layer. A special centrifuge built to consolidate clay samples has increased the capacity of the main centrifuge.

ACKNOWLEDGMENT

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