

Centrifuge modeling of an adaptive foundation system for embankments on soft soils



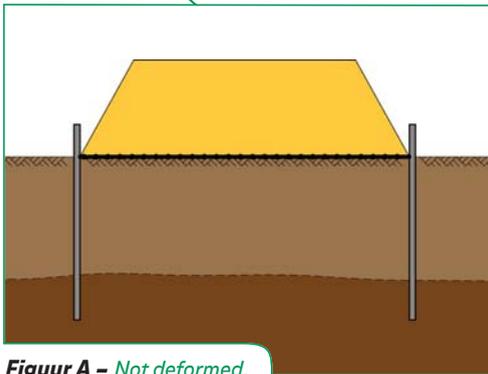
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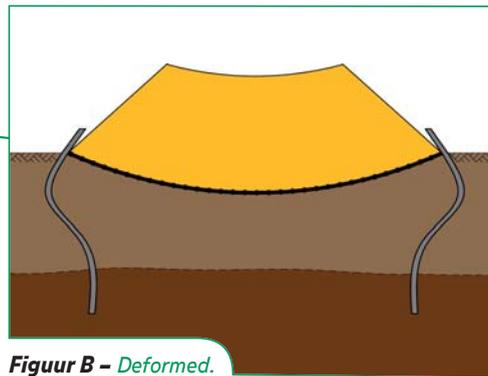
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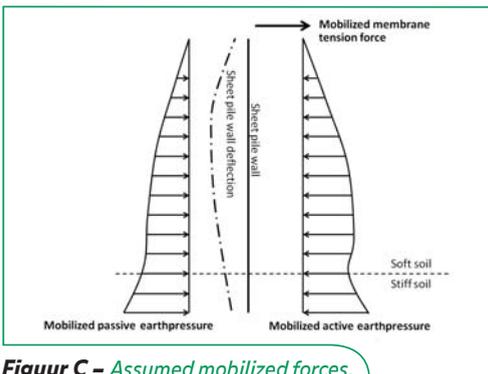
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Figuur A - Not deformed.



Figuur B - Deformed.



Figuur C - Assumed mobilized forces.

Introduction

Within a research project centrifuge tests are performed in the beam centrifuge Z1 (Jessberger & Gütler, 1988) of the Ruhr-Universität Bochum to analyze the behavior of a new adaptive foundation system for embankments on very soft soils. The measurement data from the centrifuge tests are used for the calibration and verification of a numerical model. Subsequently numerical parameter studies will be conducted with the final aim of developing an analytical calculation model for the design of the foundation system.

System behavior

The adaptive foundation system consists of two vertical and parallel walls (e.g. sheet pile walls) which are introduced at a certain distance between each other into the soft soil and connected by a tension membrane (e.g. geotextile) at the existing ground level. The vertical walls may end

within the soft soil layer or reach further down into a firm layer. The soft soil beneath the embankment is therefore confined by the vertical and horizontal elements (see figure A).

The embankment is constructed above the tension membrane. The load from the embankment onto the soft soil generates a horizontal pressure onto the vertical walls which provokes outward movements. These movements are restricted by the tension membrane. At the same time an additional tension force is mobilized within the membrane due to settlements beneath the embankment. This additional tension force leads to a further restriction of the outward movements. The foundation system ensures the global stability of the embankment (e.g. bearing failure and extrusion) and prevents or reduces the system deformations (see figure B and C).

The stress and strain of the different system components, vertical walls, tension membrane and soft soil, are strongly influenced by their interaction. Due to consolidation processes in the soft soil these interactions are time dependent. Due to the complex interaction and the multitude of parameters a comprehensive numerical parameter study is planned for the system analysis.

Model technique

For the calibration and verification of the numerical model measurement data obtained from the system is required. The centrifuge technique combines the advantages from the field and small scale tests. With the centrifuge it is possible to

generate the real stress field but at the same time having the advantage of faster consolidation due to the shorter drainage path. The following sections describe the model set-up and the centrifuge test itself.

CENTRIFUGE TEST SET-UP

PROTOTYPE GEOMETRY

The dimensions of a prototype were chosen to be a 10 m high embankment on top of a 10 m thick soft soil layer. The base width of the embankment and therefore the distance between the two vertical walls is 40 m with a slope angle of about 30°, which results in a crest width of about 5 m.

CENTRIFUGE MODEL

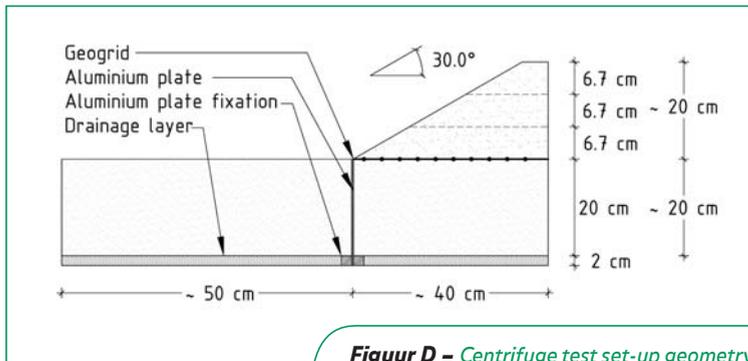
The inner dimensions of the two strong boxes used are 90 cm width, 36 cm depth and 60 cm height. One side wall is made out of acrylic glass to observe the system during the test. Half of the system is modeled in the centrifuge tests at an acceleration of 50 g by benefiting from the symmetry of the system. The thickness of the soft soil layer and the height of the embankment are 20 cm. The embankment width is 40 cm and the crest width about 5 cm. The soft soil layer is consolidated out of a Kaolin slurry. A 20 mm sand drainage layer was placed beneath the slurry.

A geotextile is located in between the sand and the slurry as a separation and filtration layer. The vertical walls are aluminum plates with a bending stiffness equivalent to prototype sheet pile walls. Down-scaled geogrids according to (Springman

Summary

The paper deals with a new adaptive foundation system for embankments on very soft soils and with its complex and time dependent interaction mechanisms of the system components. The system itself and the interactions are delineated. Due to the complexity it is planned to analyze the foundation system by means of numerical simulations. For the verification and calibration of the numerical model small scale model test at increased g -level are planned. The model set-up, test program as well as procedure of the centrifuge tests are described. For the

centrifuge tests a new sand hopper concept was developed and realized for the staged construction of the embankment during increased g -level. The funnel of the sand hopper can be also refilled in-flight. The test set-up with its instrumentation and the sand hopper was successfully tested in a first centrifuge test. In the evaluation of the first test results the interactions between the system components are clearly visible. The measurements of the system deformations are within the expected range. Further centrifuge tests are planned.



Figur D – Centrifuge test set-up geometry.

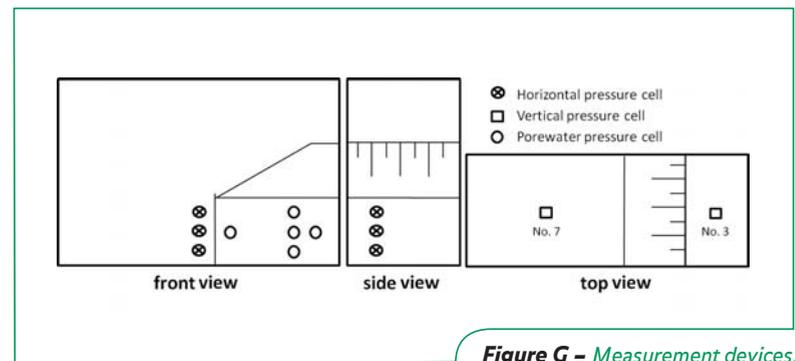


Figure G – Measurement devices.

et al., 1992) are used for modeling the tension membrane (see figure D).

The geogrid membrane is fixed to a further horizontal bar, which has three vertical steel bars attached. These three bars are placed into the steel tubes and allow for vertical movements but prevent the movements in the horizontal direction (see figure E).

The embankment is constructed in-flight. A special device was developed to allow the staged construction of the embankment in-flight which is mounted on top of the strong box after consolidation of the slurry (see figure F). The device consists of a funnel with a variable opening slit and a storage drum. The funnel is driven by a threaded rod which is attached to a motor and can move horizontally forwards and backwards along two steel bars. The speed of the funnel is fully adjustable. The opening width of the funnel was calibrated in preliminary tests to allow for a well defined and regular sand flow.

Once the funnel is empty it can be refilled in-flight from a storage drum, which has a 5 cm wide opening slit for filling and pouring. The sand volume which is poured into the funnel can be controlled by the rotation angle of the drum.

Instrumentation

During the centrifuge tests the total vertical pressure is measured by two load cells at the bottom of the box. These load cells are placed on

20 mm high blocks, so that they reach out of the drainage layer and measure the total pressure at the bottom of the soft soil layer. One load cell is placed beneath the embankment and the second load cell is placed in front of the embankment and vertical wall. The total horizontal pressure is measured by 6 further load cells. 3 load cells are installed on the center line of the back wall of the strong box and the other 3 in the side wall beneath the future embankment. Another 5 load cells are installed in the back wall to measure the pore water pressure, so the consolidation process can be monitored (see figure G).

The aluminum walls are instrumented with strain gauges at their center line. At the connection between aluminum wall and geogrid 2 load cells are installed to measure the connection forces (figure G). The weight of the connection construction is supported by steel wires. 2 displacement transducers are fixed to the top end of the aluminum wall and a draw-wire sensor is attached to the geogrid bearing device at the axis of symmetry to measure the deformations. 2 more displacement transducers measure the settlement of the Kaolin surface during the entire test.

CENTRIFUGE TESTS

SLURRY PREPARATION

Before the embankment can be constructed the soft soil has to be prepared. The soft subsoil is produced out of a Kaolin powder by mixing it with water to a water content of 100% [m/m].



Figure E – Bearing element.



Figure F – Sand hopper.

CONSOLIDATION

The slurry is consolidated in the centrifuge at 50 g preparing a normally consolidated soft soil (OCR = 1) with linear stress increase with depth. Extra consolidation weight is produced by placing customized flexible sand mattresses on top of the slurry, consisting of a sand layer in between two permeable geotextiles. Due to their flexibility a

Figure H – Stage 1, 2 and 3.



uniformly distributed load is applied to the slurry which ensures that also the upper part of the slurry is consolidated. Close to the surface an overconsolidated stress state is generated but with increasing depth OCR becomes close to 1. Since the consolidation takes a long time, two strong boxes are prepared and consolidated simultaneously in the two baskets of the beam centrifuge. After consolidation of the slurries, the centrifuge is stopped and one strong box is replaced by counterweights for the next test phase.

EMBANKMENT CONSTRUCTION

The sand mattresses in the remaining strong box on top of the Kaolin layer are removed and the excess Kaolin is extracted so the total height of the soft soil layer becomes 20 cm. The geogrid with the load cells attached is connected to the aluminum plate and the hopper mechanism is mounted. After spinning up the model to 50 g and a reconsolidation phase of about 1 hour the embankment is constructed in 3 stages. In each stage a layer thickness of 1/3 of the final height is poured. A consolidation phase follows after each consolidation step.

TEST PROGRAM

For the calibration of the numerical model it is necessary to analyze different system configurations. It is planned to vary the stiffness of the tension membrane as well as of the vertical structural elements. Therefore two geotextiles with the same geometrical shape but different stiffness are used. Geotextile one is Polyester and the second geotextile is Polyvinylalcohol, which is about seven times stiffer than the first geotextile. The vertical structural elements are simulated by aluminum plates with a thickness of 2 mm and 4 mm. Furthermore the stability of the structural elements was alternated. A test without the geotextile element and a test without the vertical element are planned. A total of seven tests will be conducted, with one configuration tested twice to quantify the reproducibility of the measurement data.

Test Results

In the first centrifuge test a configuration of the foundation system with the polyester geogrid and 4 mm thick aluminum wall was tested. The consolidation of the slurry took 12 hours. After the consolidation phase the strong box was modified for the next phase. After reaching the increased g-level of 50 g the slurry inside the strong box was reconsolidated for 1 hour before the first sand layer was installed by the sand hopper. Between each construction step of the embankment the soil consolidated for one hour. The successful construction of the embankment can be seen in figure H.

Figure I shows the total vertical pressure at the bottom of the soft soil layer during the phase of embankment construction. Pressure cell 7 is located in front of the aluminum wall and pressure cell 3 behind the wall and beneath the embankment. Pressure cell 7 shows a constant vertical pressure of about 150 kN/m² which more or less was expected at an acceleration of 50 g and a height of the soft soil of 20 cm with a density of about 15 kN/m³. The response of pressure cell 3 clearly shows the three construction stages of the embankment. The embankment thickness above load cell 3 had a thickness of about 6 cm in the first construction stage, about 8.9 cm in the second stage and about 13 cm in the last stage, which means the final height of 20 cm was not reached in the first test due to minor issues with the remote control of the funnel. With a bulk density of about 16 kN/m³ for the sand, the theoretical total load increase is about 48 kN/m² in the first stage, 23 kN/m² in the second stage and 33 kN/m² in the last stage. This corresponds quite well with the measured increase of about 52 kN/m² in the first stage, 26 kN/m² in the second and 30 kN/m² in the last stage.

It can be observed that in each load stage the total load slightly reduces over time. At this stage of the test program it is not clear if this observation is based on measurement inaccuracies, soil mechanical processes, boundary effects or

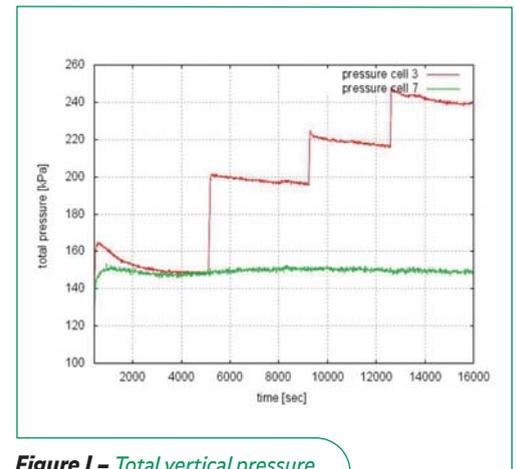


Figure I – Total vertical pressure.

the system itself. Possibly compaction of the soil resulted in an increase of the soil strength and stiffness, which would result in a greater load spreading and therefore in a reduction of the effect on the vertical stresses with depth. But since the load is placed over the entire box width, this explanation seems unlikely. Boundary effects may have caused an increase in wall friction as consolidation took place. However this effect was previously analyzed by compression load tests under a static, incrementally increased hydraulic load. The difference between compression load and measured stresses beneath the soft soil layer have been negligible. It is also possible that the vertical pressures are reduced due to the tensile force mobilization in the membrane.

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