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

O. Detert
HUESKER Synthetic GmbH & Ruhr-Universität Bochum
D. König, T. Schanz
Ruhr-Universität Bochum

Abstract: Centrifuge tests will be conducted to analyze the behavior of a new adaptive foundation system for embankments on very soft soils. The embankment will be constructed in-flight in three stages. Various measurements are to be taken during the test, which will later be used for the calibration and verification of a numerical model. This paper describes the new adaptive foundation system as well as the centrifuge test set-up and the tests them self. A special focus is put on a newly developed sand hopper concept, which allows the construction of the test embankment in stages and refills the movable funnel in-flight from a storage drum.

Keywords: Sand hooper, adaptive foundation system, embankment, geogrid, sheet pile walls

1 INTRODUCTION

1.1 Aim

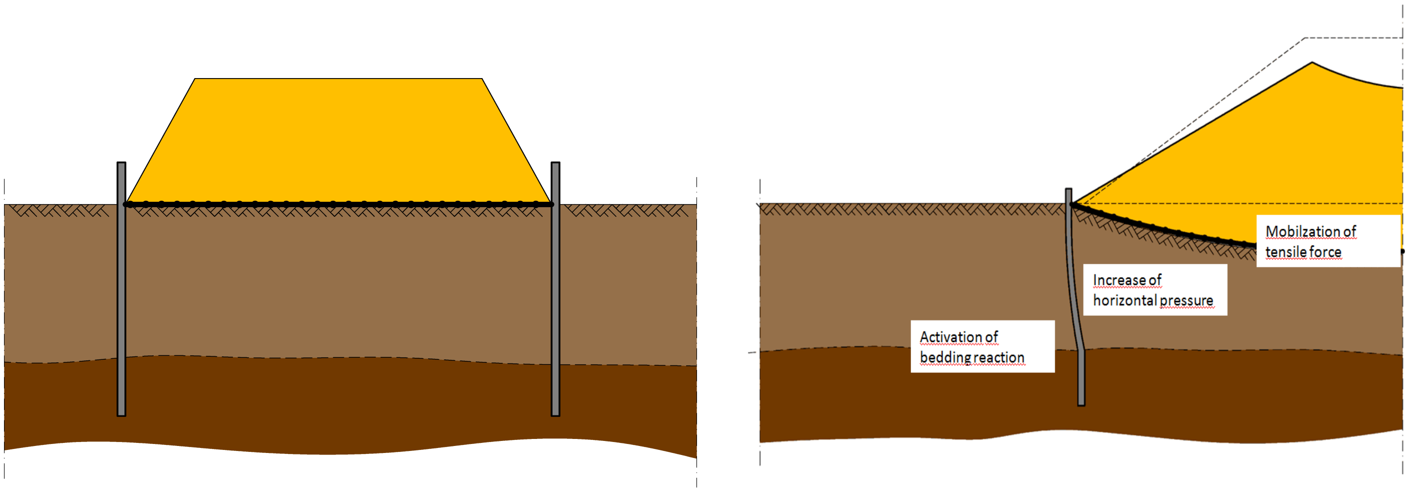
Within a research project centrifuge tests are planned to be performed in the beam centrifuge Z1 of the Ruhr-Universität Bochum to analyze the behavior of a new adaptive foundation system for embankments on very soft soils. The measurement data from the centrifuge tests will be used for the calibration 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.

1.2 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 to each other 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 1a).

The embankment will be 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 1b).

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. So the stiffness of the soil as well as the total stress on the walls are changing with the consolidation from undrained condition at the beginning of the embankment construction to drained conditions in the final state. The system behavior strongly dependends on the distance between the vertical walls, their



(a) undeformed

(b) deformed

Figure 1. System sketches

length and degree of fixation. Furthermore on the thickness and stiffness of the soft soil layer as well as the stiffness of the vertical walls and tension membrane and the relation of the latter both between each other. Due to the complex interaction and the multitude of parameters a comprehensive numerical parameter study is planned for the system analysis.

1.3 Model technique

For the calibration and verification of the numerical model measurement data obtained from the system are required. A full scale field test would generate the most reasonable data but the boundary conditions are hard to control and it is very time consuming, especially due to the long consolidation times. Small scale tests in the laboratory have the great advantage of controlled boundary conditions, reproducibility, less time consuming and less cost intensive. Their recognized drawback however is the reproduction of realistic stress states. The centrifuge technique combines the advantages from the field and small scale test. With the centrifuge it is possible to generate the real stress state but at the same time having the advantage of faster consolidation due to the shorter drainage path. The following chapters will describe the model set-up and the centrifuge test itself.

2 Centrifuge test set-up

2.1 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.

2.2 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 will be 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 will be 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 drainage layer of 20 mm sand is 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 out of aluminum plates with bending stiffnesses equivalent to prototype sheet pile walls. Down-scaled geogrids are used for modeling the tension membrane (see Figure 2).

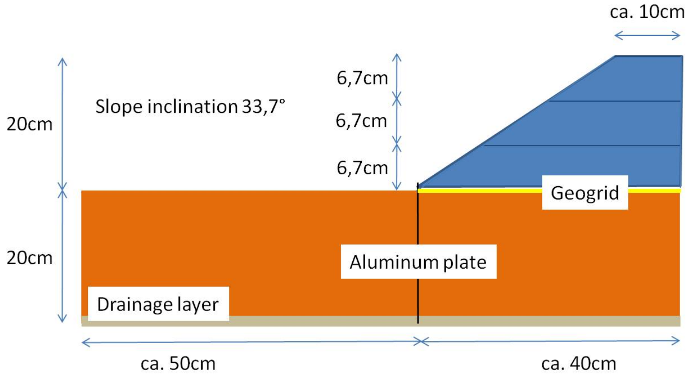


Figure 2. Centrifuge test set-up geometry

At the axis of symmetry a special bearing was developed. The bearing system consists of three steel tubes which are fixed to the strong box side wall and filled with grease. 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 3).

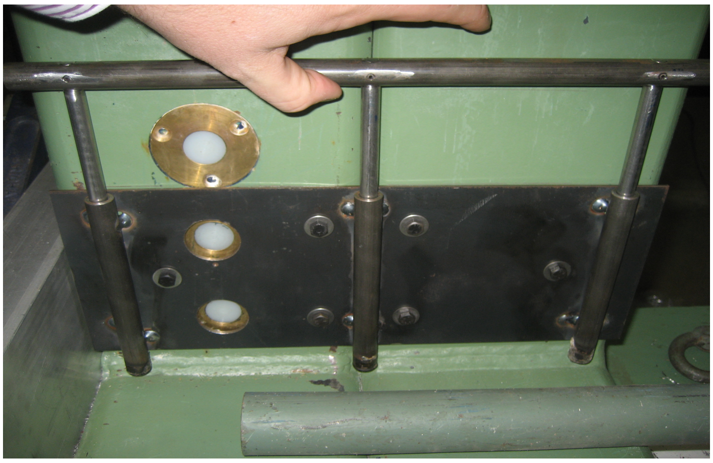
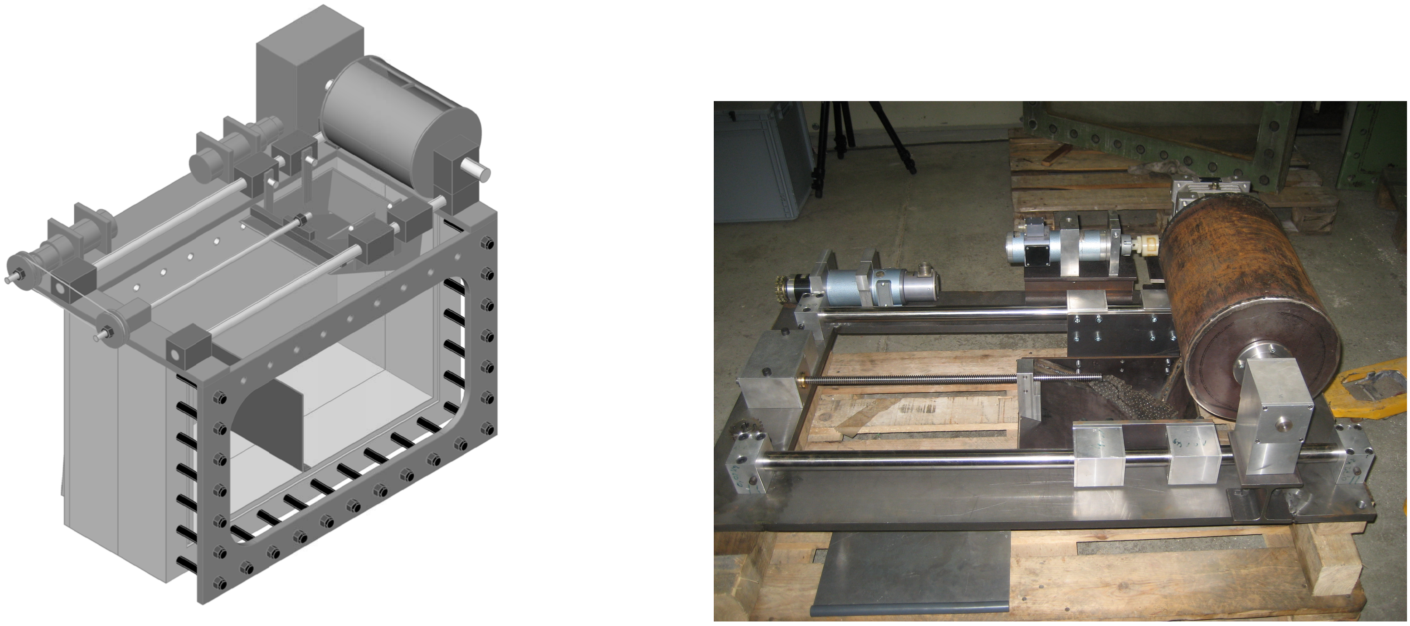


Figure 3. Bearing element

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 4). 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.

The geometry of the embankment is controlled by varying the speed and/or direction of the funnel. 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 funnel has to be located beneath the storage drum at the side wall of the strong box to be refilled. At the level of the opening slit of the funnel a sponge rubber is fixed to the side wall, which prevents the sand flow by closing the opening slit. Once the funnel is parked in this position the drum can be turned around its axis by a second motor. The sand volume which will be poured into the funnel can be controlled by the rotation angle of the drum. Due to the opening in the drum surface and the slope of the sand inside the drum, which occurs during the rotation of the drum, a certain imbalance does develop. This imbalance provokes a hard to control rotation velocity of the drum, which was overcome by applying an additional weight close to the drum opening to reduce the imbalance.



(a) (b)

Figure 4. Sand hopper

2.3 Instrumentation

During the centrifuge tests the total vertical pressure are measured by two load cells at the bottom of the box. These load cells are placed on twenty millimeter 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 six further load cells. Three load cells are installed on the center line of the back wall of the strong box and the other three in the side wall beneath the future embankment. Furthermore five load cells are installed in the back wall to measure the pore water pressure, so the consolidation process can be monitored. These load cells are arranged at the end of a small chamber which is separated from the soft soil by filter stones, so only water can penetrate inside the chamber. Two valves at each chamber on the very top and bottom allow for de-airing of the chamber by flushing it with water. The aluminum walls are instrumented with strain gauges at their center line. At the connection between aluminum wall and geogrid two further load cells are installed to measure the connection forces. Two 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. Further two displacement transducers measure the settlement of the Kaolin surface during the entire test.

3 Centrifuge tests

3.1 Slurry preparation

Before the embankment can be constructed the soft soil has to be prepared. The soft subsoil will be produced out of a Kaolin powder by mixing it with water to a water content of 100%, which has proven in preliminary tests to produce the best consistency of the slurry for the following steps: The slurry is carefully mixed by an agitator at a relative low speed, to minimize the air entrainment. At the same time the strong box is equipped with the different pressure cells, the aluminum wall is installed and the drainage layer is placed. One end of the geogrid is connected to the bearing at the axis of symmetrie and the other end is temporally fixed at the side wall of the strong box. The strong box is filled with water before the slurry is finally filled in by the contractor procedure.

3.2 Consolidation

The slurry will be consolidated in the centrifuge at 50 g preparing a normally consolidated soft soil (OCR $\approx$ 1) with linear stress increase with depth. Extra consolidation weight is produced by placing customized flexible sand mattresses on top of the slurry, consisting out of a sand layer in between two permeable geotextiles. Due to their flexibility an uniformly distributed load is applied to the slurry which ensures that also the upper part of the slurry will consolidate. 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 simultaneous in the two baskets of the beam centrifuge. After consolidation of the slurries, the centrifuge will be stopped and one strong box is replaced by counterweights for the next test phase.

3.3 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 including the load cells are 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 $\frac{1}{3}$ of the final height is poured. After finishing of one stage a consolidation period follows.

3.4 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 geotextile types with the same geometrical shape but different stiffnesses will be used. Geotextile one is made out of the raw material Polyester and the second geotextile made out of Polyvinylalcohol, which is about seven times stiffer then the first geotextile. The vertical structural elements will be simulated by aluminum plates with a thickness of 2 mm and 4 mm. Furthermore the degree of fixity of the structural elements will be alternated. To identify the influence on the geometrical relation of the construction, especially the embankment height, the embankment will be constructed in three stages. After each construction step follows a consolidation phase. To reproduce realistic data the embankment will be constructed in-flight. Stopping the centrifuge to built up the embankment and restart it afterwards results in a decrease and increase of the stresses in the soil or better said in an unloading and reloading process, which changes the stress state in the soil and also the soil response, since the soil behavior is path dependent. All together seven tests will be conducted, with one configuration tested twice to quantify the reproducibility of the measurement data. The prototype and model dimensions are listed below (see table 1).

	Prototype	**50 g model**	**Unit**
Soft soil layer thickness	10	0.20	m
Embankment height	10	0.20	m
Embankment width	40	0.80	m
Crest width	5	0.10	m
Bending stiffness vertical elements			
4 mm wall	46625	0.373	kNm^2/m
2 mm wall	5875	0.047	kNm^2/m
Geogrid stiffness			
Polyester	5050	101	kN/m
Polyvinylalcohol	37000	740	kN/m

Table 1. Prototype and model dimensions

4 Test results

In a 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 again 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 succcesful staged construction of the embankment can be seen in Figure 5.

(a) Stage 1 (b) Stage 2 (c) Stage 3

Figure 5. Construction Stages

Figure 6 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/m^2 which more or less was expected at an accelaration of 50 g and a height of the soft soil of 20 cm with a density of about 15 kN/m^3. 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. With a density of about 16 kN/m^3 of the sand the theoretical total load increase is about 48 kN/m^2 in the first stage, 23 kN/m^2 in the second stage and 33 kN/m^2 in the last stage. This corresponds quite well with the measured increase of about 52 kN/m^2 in the first stage, 26 kN/m^2 in the second and 30 kN/m^2 in the last stage.

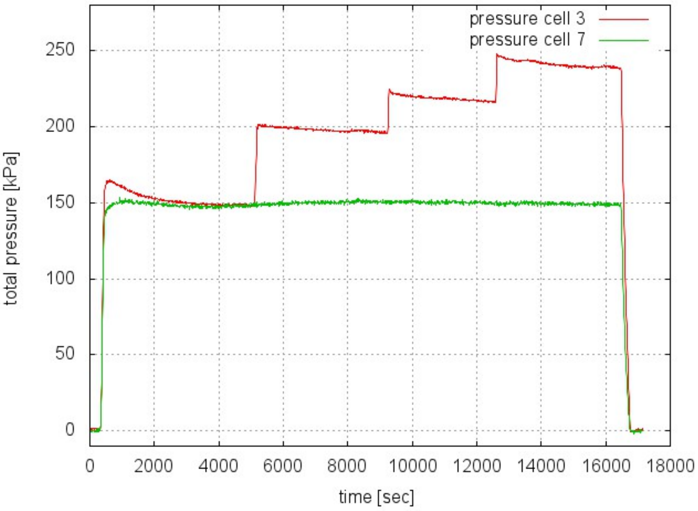


Figure 6. Total vertical pressure

It can be observed that in each load stage the total load does slightly reduce over time. At this stage of the test program it is not clear if this observation is based on measurement inaccuracies, on soil mechanical processes, boundary effects or the system itself. Possible soil mechanical processes could be 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 does not seem to be right. Boundary effects could be an increase in wall friction with increasing consolidation degree, whereas this effect was previously analyzed by compression load tests under a static, stepwise 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.

Figure 7 shows the relation between the vertical settlement of the embankment at the axis of symmetrie and the horizontal deformation of the aluminum plate at the level of geogrid connection. During the reconsolidation phase settlements occcur beneath the embankment but no horizontal deformation of the aluminum plate, which results in a with time increasing ratio. The installation of the sand layers provokes time dependent outward movements of the aluminum wall and further settlements beneath the embankment, whereas the ratio between the both deformation seams to stay at a constant value. It is assumed at this moment of the test program that the constant value does exist and depend on the ratio between the bending stiffness of the aluminum wall and the tensile stiffness of the geogrid.

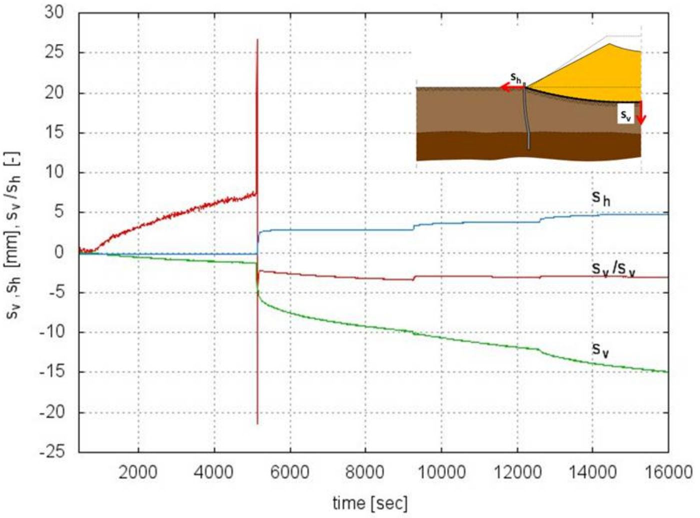


Figure 7. Deformations of the system

To back up the described observations furter centrifuge tests have to be performed.

5 Summary

The paper deals with a new adaptive foundation system for embankments on very soft soils and with its complex and time dependent interactions 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 total and pore water pressures as well as the system deformations are within the expected range. Further centrifuge tests are planned.