Analysis of a self-regulating foundation system for embankments on soft soils by means of centrifuge tests and numerical simulations

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ABSTRACT: A new innovative foundation system for embankments on soft soils is currently being analyzed at the Ruhr-Universität Bochum, Germany, in cooperation with HUESKER Synthetic GmbH, Germany. The foundation system consists of two parallel vertical walls, which are installed into the soft subsoil and connected at ground level via a horizontal geosynthetic reinforcement which acts as a tension membrane (further called tension membrane). The embankment is constructed on top of the tension membrane. The system ensures global stability, controls the horizontal deformation and reduces the horizontal thrust in the subsoil on either side of the embankment. The complex interactive system behaviour is analyzed by centrifuge model tests and numerical simulations. Results of the centrifuge model tests are presented and interpreted in this paper. Conclusions and presumptions from the measurements of the centrifuge tests will be analyzed and verified thereafter by numerical simulations. One of the main findings is the activation of an arching mechanism within the embankment even with the relatively low ratio of 0.25 between the final embankment height and base width. The relevance of this mechanism for the design will be discussed at the end of this paper.

Keywords: geosynthetic reinforcement, foundation system, soft soil, embankment, centrifuge, numerical methods

1 INTRODUCTION

The construction of embankments on very soft soils e.g. for transportation, breakwaters or stockpiles, is a challenge due to the low shear strength, low permeability, high compressibility and high water content of the subsoil. The surcharge load imposed by the embankment can not only result in a local or total loss of stability, but also in unacceptable settlements and horizontal deformations or thrust, which could endanger nearby structures. To overcome these problems, different construction methods are applicable. However, each method has its limitations however, which can be related to the thickness of the soft soil layer, height of the embankment, time and cost constrains as well as ecological or technical reasons.

1.1 *Conventional construction methods for embankment on soft soils*

Conventional methods include, for example, partial or total soil replacement, the construction of the embankment in stages, with or without basal reinforcement and/or with or without vertical drains, and the application of lateral berms which can be used in combination with the aforementioned solutions. Furthermore, the embankment can be constructed on pile-like elements such as conventional or geotextile encased granular columns, stabilized soil columns or concrete piles. Deploy of light weight material is also possible.

The aim of the soil replacement method is to increase the shear strength by replacing unsuitable soils with suitable fill material and hence reduce the failure potential as well as deformations of the embankment.

When constructing the embankment in stages, for each stage the soft soil is loaded only as much as the current shear strength of the soft soil allows. With progressing consolidation the soft soil gains shear strength due to the increase in effective stresses, thereby allowing higher loads to be placed subsequently. Vertical drains accelerate the consolidation process whereas basal reinforcement layers significantly reduce the induced shear stress in the soft soil especially beneath the embankment slopes (Jewell (1988), Rowe and Li (2005)).

Lateral berms increase the stability as they act as a counterbalance load on each side of the embankment and therefore reduce deformations and increase safety against failure.

When using pile-like elements the load of the embankment is mainly transferred by these elements through the soft subsoil into deeper more competent soil layers and the soft subsoil is stressed less. Granular columns also partly act like a partial soil exchange.

With the use of light weight materials the stresses on the soft subsoil are reduced resulting in an increased safety against failure as well as reductions in deformation.

Constraints and disadvantages of the different construction methods can be summarized according to Almeida and Marques (2013) as follows:

Partial or total replacement of soft soil: A valid technique for uncontaminated soft soils up to a thickness of about 4 m coupled with nearby disposal areas. Quality control is difficult, since the complete removal of the soft material cannot be guaranteed, which may result in future differential settlements. Furthermore, the high volume of disposal material and issues of sustainability are both seen as potential disadvantages.

Staged construction with or without additional measures: Cost effective but can be time and (in case of lateral berms) space consuming, and not a settlement-free method. This solution can also require large amount of earthworks, especially when surcharge loads are used.

Embankment on pile-like elements: Depending on the used elements, a nearly or complete settlement free but expensive construction method.

Light weight material: Mostly related to relatively high costs. Depending on the material used, different additional measures have to be taken to protect the material against environmental influences. Not to be used beneath water level without sufficient surcharge load, due to buoyancy risks.

1.2 *New self-regulating foundation system*

The new self-regulating foundation system (Figure 1) 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 with a negligible bending, but a high tensile stiffness (e.g. high-strength geogrid or woven/knitted geotextile) at the existing ground level. The vertical walls may end within the soft soil or extend down into a competent layer. The soft soil beneath the embankment is therefore confined by the vertical and horizontal elements. The embankment is constructed above the tension membrane. The load from the embankment over the soft soil generates a significant 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 tension membrane due to deflections beneath the embankment. This additional tension force may lead to a further restriction of the outward movements.

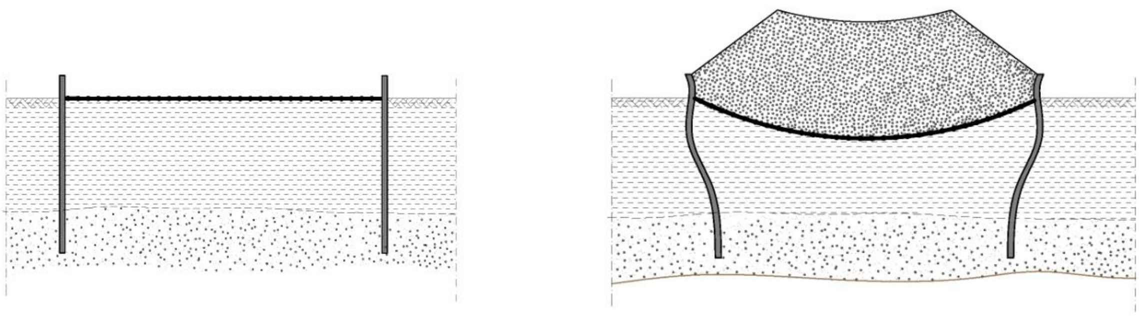


Figure 1. Sketches of self-regulating foundation system in the unloaded stage (left) and loaded stage (right, exaggerated deformation)

The new self-regulating foundation system can be used within soft soils of any thickness without the need of any soil disposal to ensure the local and global stability of the embankment, e.g. bearing failure and extrusion and to control its deformation. The embankment can be constructed to its final height in one stage. Equally distributed settlements do occur over time and lateral deformations as well as horizontal thrust in the soft soil on nearby structures can be controlled and significantly reduced. The required construction space can be considerably reduced by different system configurations, e.g. extension of the sheet pile wall above ground level by a couple of meters. The vertical elements of the system can be partly or completely reclaimed over time and reused, which can have a noticeable beneficial effect on the overall costs of the embankment construction.

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. The stiffness of the soil as well as the total stresses on the walls are changing through consolidation, from undrained conditions at the start of embankment construction, to drained conditions in the final state. The system behaviour strongly depends on the embankment height, the distance between the vertical walls, their length and degree of fixation. Furthermore, it depends on the thickness, shear strength and stiffness of the soft soil layer as well as the bending stiffness of the vertical walls and tension stiffness of the membrane and the relationship of the last two parameters between each other. A detailed description of the theoretical system behaviour can be found in Detert et al. (2013).

1.3 *Research strategy*

For a sound design of the system it is important to know and understand the stress and strain evolution over time on above mentioned factors and relations. Due to the complex and time dependent interaction and the multitude of influencing parameters a comprehensive numerical parametric study is planned for the system analysis. For the validation of the numerical model measurement data are required to demonstrate its capability of reproducing the main mechanisms of the self-regulating foundation system. With a series of centrifuge model tests, some principle configurations of the systems are analyzed, before starting a systematic investigation by numerical simulations.

In the next section, results from the centrifuge tests are presented and interpreted. Conclusions and presumptions from these tests are analyzed and verified thereafter by means of numerical simulations.

2 CENTRIFUGE TESTS

Within the centrifuge test apparatus four different system configurations are tested at an increased g-level of 50g. Only half of the foundation system requires model simulation, due to the symmetry of the system. The embankment is constructed in three stages by means of a refillable and moveable sand hopper. Each construction stage is followed by a consolidation phase of about 1 hour. A detailed description of the centrifuge test set-up, instrumentation and execution is given by Detert et al. (2014).

2.1 *Categories of model tests*

For the centrifuge tests some adaptations had to be done compared to reality, which mainly concern the bearing of the tension membrane at the axis of symmetry as well as the connection between the geotextile membrane and the model wall. It was observed that some activation deformation within the first construction step of the embankment occurs to overcome some slack in the system, which could not be avoided even taking the greatest care during model preparation. This slack is mainly compensated by larger settlement at the very beginning of the pouring process. The wall deformation itself is not influenced by the slack.

2.2 *Test results*

Figure 2 shows the sequence of embankment construction at an acceleration level of 50g. The toe of the embankment is in direct contact with the upper edge of the model wall, which exceeds the surface of the soft clay. A slightly deformed clay surface is visible at the first construction step. With increasing time and height of the embankment settlements of the clay surface are observed (sand becomes dark due to water saturation), which show a maximum in the middle of the system (axis of symmetry, side wall of strong box). Compared to a conventional basal reinforced embankment, where significant settlements can be also observed under the toe of the embankment, in this case the settlement contours vanish towards the model wall. This demonstrates the influence of the combined system of the walls connected with the tension membrane on the deformation behaviour.

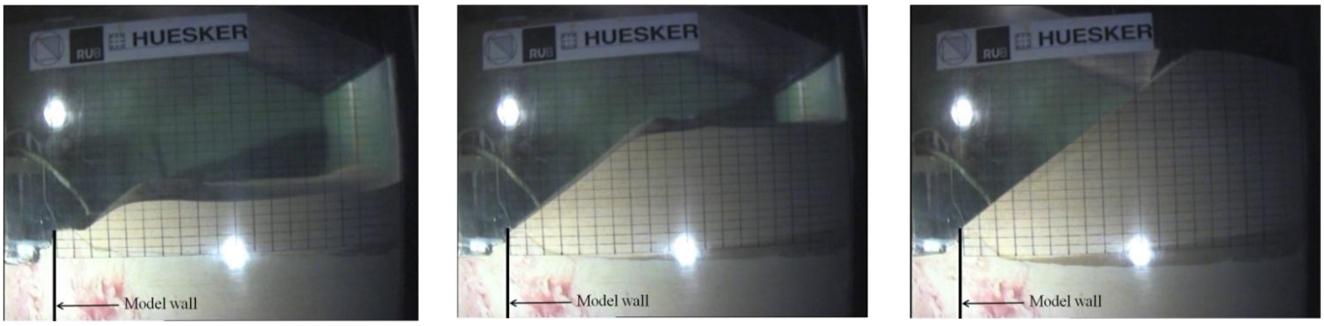


Figure 2: Construction of the embankment under increased acceleration in three stages. First step on the left, second step in the middle and last step at the right. Black line indicates location of the vertical model wall

The readings of the total stress cell, located below the embankment at the bottom of the clay layer are presented in Figure 3 (black triangle). The measured total vertical stress is plotted versus time. The origin of the time axis corresponds to the start of the centrifuge. First, the reconsolidation of the clay has taken place before the embankment is constructed in three stages. After the third consolidation phase the tension membrane was cut by an electric wire.

The pressure cell below the embankment detects at the beginning a constant stress. With construction of the embankment the total stress is increasing. Examining the total vertical pressure over the time, it can be observed, that in each consolidation phase a decrease of the total pressure takes place. The decreases are about 12% in the first consolidation phase, 22% in the second phase and approximately 46% in the third phase of the respective stress increases due to the construction steps. The influence of the membrane can be back-analyzed based on its tensile stiffness and registered deformed shape. Approximately 2% (0.5 kPa) of the total reduction in total vertical stress can be explained by the tension membrane action. This relatively small value results from the small deflection of about 2 cm on a 40 cm (model dimension) wide embankment base and the small elongation due to outward wall displacement of about 0.5 cm at the connection point with the tension membrane.

The soft soil is compressed by the settlement depression and pore water extruded. Assuming a very dense state of the sand, the amount of extruded water which is assumed to run off and therefore reduce the vertical pressure is approximately a further 16% (5.2 kPa) of the total reduction in total vertical stress. This means by tension membrane action and water extrusion the total reduction of total vertical stress can not be explained.

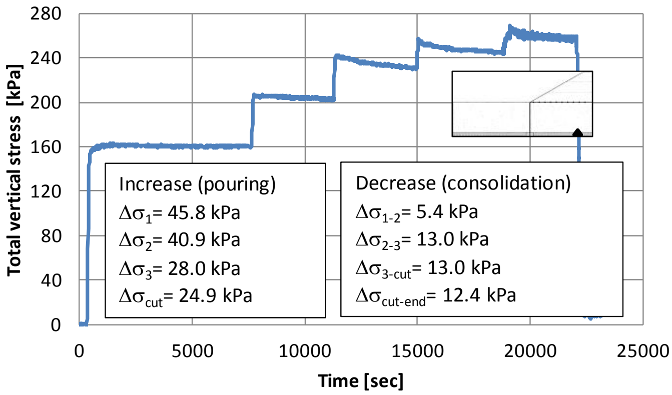


Figure 3: Readings of total pressure cell (black triangle) during reconsolidation and embankment construction versus time (model dimensions)

The clear tendency of increasing stress reduction with increasing embankment height does allow for the hypothesis that a kind of arching mechanism is activated within the embankment due to the settlement and the stiffening and confining effect of the vertical wall in conjunction with the tension membrane. This becomes quite obvious when the tension membrane is cut by the electric wire. Immediately following rupture of the tension membrane, a sudden stress increase of 24.9 kPa is observed. Approximately 0.5 kPa was captured before by the membrane which means the remainder of the load was transferred via the arch into the model wall.

The sum of the decrease of the total vertical stresses for the three consolidation phases is 31.4 kPa. The stress reduction due to membrane deflection and elongation is 0.5 kPa and 5.2 kPa due to water extrusion.

The difference of 31.4 kPa – 5.7 kPa = 25.7 kPa is attributed to arching. Comparing these values with the stress increase of 24.9 kPa due to the cutting of the geotextile shows good agreement with the numbers, whereas it has to be clarified if load from consequent construction steps are transferred via the activated arching mechanism directly into the wall and not captured by the pressure cell.

Again a reduction in vertical stress is observed in the consequent consolidation phase. After the tension membrane has been cut, the wall deformation does increase significantly (from 6.5 mm to 16.7 mm), before it is restrained by the physical measurement installations within the strong box. A new arch can develop supported by the restrained wall and the original tension membrane fixation which is still on the inner side of the vertical wall.

2.3 *Conclusions of this section*

An arching effect was derived by measurement results over time. It was found in this section that an arching effect can explain the observed behaviour of the vertical stress over time. The presumption and conclusions of this section will be analyzed and confirmed in the next chapter by means of numerical methods.

3 NUMERICAL SIMULATIONS

Numerical methods are a powerful tool for analyzing complex mechanisms with varying parameters. With numerical parametric studies the sensitivity of different parameters and their impact on the stress and strain of different system components can be analyzed. The right choice of the constitutive soil model and the validation of the numerical model are important parts for the numerical simulation process.

The constitutive soil model has to be capable of reproducing significant soil mechanic processes occurring in the system due to the centrifuge test procedure, load history or the construction steps with subsequent consolidation phases. The data obtained from the laboratory and centrifuge tests can be used to confirm the choice of the correct constitutive soil model.

3.1 *Choice of soil model*

Numerous constitutive soil models are available, which differ in their features, such as the consideration of creep, anisotropy, destructuration or different hardening laws. The choice of the soil model depends on the dominant phenomena which have to be considered in the numerical simulations. The aim of these numerical simulations is to analyze the executed centrifuge tests and to confirm or reject the original conclusions and hypotheses.

3.1.1 *Anisotropy and destructuration of clays*

In laboratory tests it was found that undisturbed samples of natural clays show a different behaviour than remoulded samples. Undisturbed clay samples achieve higher strength and deformation moduli then remoulded clay samples. This is due to the fact that within the natural clay an inter-particle bonding exists between the particles (Burland, 1990), which results from the mineralogy and pore-water composition combined with complex geochemical processes over time (Yildiz et al. 2009). Due to plastic straining the inter-particle bonds are progressively destroyed, this process is called destructuration (Leroueil et al. 1979).

Karstunen et al. (2005) found that the consideration of destructuration is less important for the prediction of deformation of an embankment on soft soil, whereas an observed decrease in undrained shear strength during the consolidation process could be explained by the destructuration processes. Disregarding the anisotropy can result in under-prediction of deformations.

In the conducted centrifuge tests the soft subsoil is produced from a Kaolin powder mixed with 100% water and subsequently consolidated in the centrifuge at the same g-level as the consequent centrifuge tests (Detert, 2012). The clay used in the centrifuge test is therefore at the most only five days “old” and has not been subjected to overburden pressure. Therefore it is a normally consolidated young clay and destructuration effects for this clay are considered as negligible.

At this stage the effect of anisotropy regarding shear strength and stiffness is not taken into account. The influence of the anisotropy on the system behaviour has to be evaluated at a later stage. For the time being it is assumed to be less important for analysing the fundamental system behaviour, since this depends not only on the properties of the soft subsoil but also of the structural elements.

3.1.2 *Creep*

Creep plays an important role for the long term behaviour of clay. In general the role of creep in centrifuge tests is not fully evaluated yet and further testing is recommended by Garnier et al. (2007). However, bearing in mind that the same stress is acting on the soil as in nature and consolidation processes are only speed up due to the reduced thickness of the soil layer and not due to the fact that the soil is within a centrifuge (Taylor, 2005) it is assumed, that creep does not play an important role for the system behaviour in the centrifuge tests, especially since the duration of such a test is only six to eight hours.

3.1.3 *Small strain stiffness*

A further observed property of soil is the high stiffness at low strain (strain ranges up to 10^{-3}) which is, for example, included in the hardenings soil small strain stiffness model (HSS) (Benz, 2006). It is reported that the consideration of small strain stiffness is very important, especially for deformation analysis of rigid retaining structures or foundation systems for buildings. The deformations occurring within the self-regulating foundation system during the centrifuge test are rather large in comparison of what is considered small strain stiffness. Therefore this effect is not considered to play a dominant role for the overall system behaviour.

3.1.4 *Conclusion considering choice of soil model*

In conclusion the effects of destructuration, creep, anisotropy and small strain stiffness are considered to be less important for back analyzing the main processes within the self-regulating foundation system during the centrifuge tests. The main soil mechanical processes which occur due to the loading, unloading and reloading during the subsoil preparation and test execution are well captured by the hardening soil model (Schanz, 1998), which will be used for the numerical simulations of the centrifuge tests.

3.2 *Numerical simulation*

As described in section 2 an arching mechanism was detected by the interpretation of the measurement results from the centrifuge tests. By means of numerical simulations these conclusions/presumptions are to be analyzed.

3.2.1 *Model set-up*

The numerical simulations are conducted with the software Plaxis 2012. The numerical model has the dimension of the centrifuge test set-up (Detert et al. 2012). Within the numerical simulation all steps of the centrifuge tests are replicated, whereas simplifications have to be made for the consolidation phase of the slurry. For this phase the final height of the consolidated soft soil layer is used. The increased g-level in the centrifuge tests is simulated by increasing the self-weight of the materials.

3.2.2 *Arching*

To check on the hypothesis of arching within the embankment, calculations are performed where the embankment is simulated (I) as a vertical load and (II) as frictional granular material. No arching can occur in case of simulating the embankment weight by an equivalent vertical load whereas within a frictional granular material the development of arching is possible.

Figure 6 shows the distributed vertical stresses along in the embankment base on the primary y-axis starting at 0.5 m from the vertical wall towards the axis of symmetry at 0.9 m (model dimensions). For the calculation where the embankment is simulated as a vertical load only the stress distribution after consolidation is shown. For the simulation with frictional granular material, the stress distribution is shown before and after the consolidation. On the secondary y-axis the ratio between the stress distribution of the simulation with a vertical load and the one with frictional granular material after consolidation is shown. The dashed line indicates where this ratio would be 1.0. The blue line represents the vertical stresses in the embankment base, when modelling the embankment as a vertical load. As expected the stress distribution is affine to the embankment geometry, no redistribution of the vertical stresses takes place. The black line represents the vertical stresses for the frictional granular material before consolidation.

It can be observed that the maximum value of the vertical stresses at the embankment axis of symmetry equals the vertical stresses in case of simulating the embankment as a vertical load. The agreement vanishes with increasing distance from the axis of symmetry towards the embankment slope.

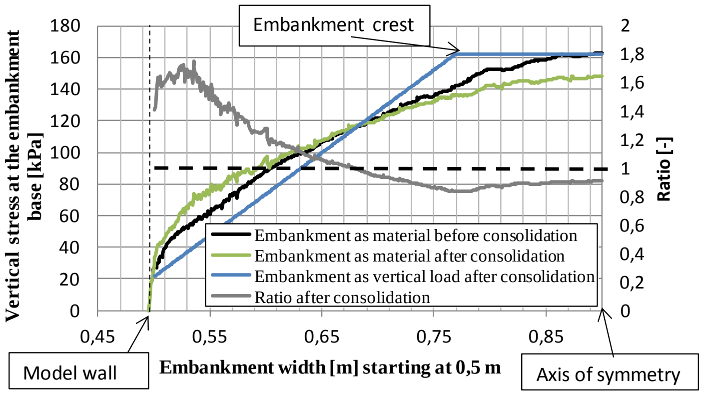


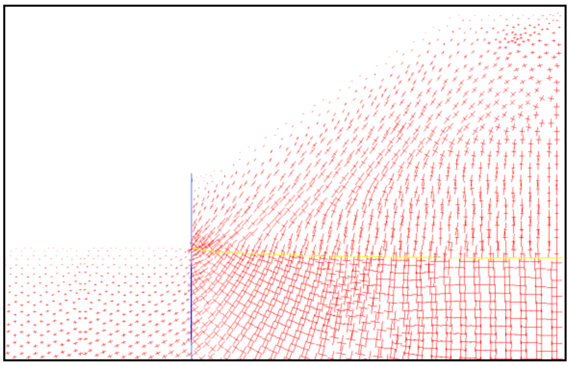
Figure 6. Vertical stress distribution at the embankment base for simulating the embankment as a vertical load or frictional granular material respectively. Furthermore the ratio between both systems is shown on the secondary y- axis.

This is addressed to two different effects, namely spreading and arching. Spreading occurs in slopes due to the fact that the horizontal forces in a vertical slice of the slope are not in equilibrium**.** Whereas the extension of the vertical model wall above ground level acts as a support to withstand the spreading forces which may enhance the load redistribution, respectively arching towards the toe of the slope and vertical model wall.

The green line represents the vertical stress in the embankment base, when modelling the embankment as frictional granular material after consolidation. Comparing the stress distribution for the frictional granular material before and after consolidation it can be observed that a reduction takes place in the mid part of the embankment and an increase within the slope of the embankment, which indicates load redistribution. This behaviour explains the reduction in vertical stress as presented in section 2.

The grey line represents the ratio between the vertical stresses for simulating the embankment with granular material and as a vertical load. Beneath the embankment crest a reduction of about 10% of the acting vertical load for the frictional granular material occurs, where as an increase of up to 80% can be observed in the embankment slope. This load redistribution is allocated to arching enhanced by spreading within the embankment fill.

Figure 7a shows the principal stresses within the embankment. The blue vertical line represents the sheet pile wall and the yellow line the tension membrane. A rotation of the principle stresses due to spreading forces and arching in the embankment can be observed close to the connection of the tension membrane and vertical wall. Comparing the settlement depressions (normalized by the maximum value) of an embankment founded by means of the new self-regulating system with one founded directly on the soft soil without any measures, it becomes obvious that the biggest differences between both are in the zone where the geotextile is connected to the vertical wall. The reduced settlements in this area can be interpreted as a stiffer behaviour due to the system. Looking at the principle stresses within the embankment it becomes obvious that the base of the arch lies within this "stiffer" zone.



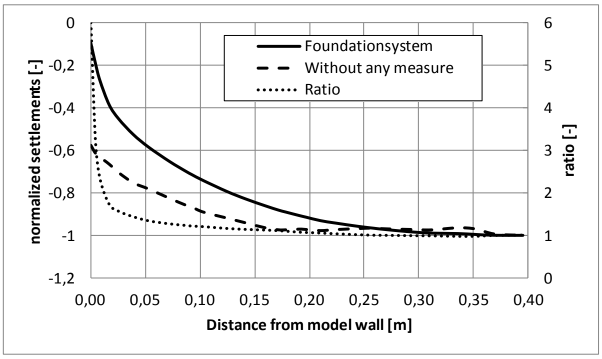


Figure 7 a/b. The left figure shows the orientation of the principal stress within the embankment and soft soil. The blue line indicates the model wall and the yellow line the tension membrane. The right figure shows the settlements (normalized by the maximum value) occurring in the embankment base when applying the foundation system and when construction the embankment without any measures and the ratio between both depression curves.

This fits well with the theory of arching, i.e. that stiffer components of a system attract loads (e.g. Terzahgi (1943), Zaeske (2001), van Eekelen et al. (2013)). The arching is likely be enhanced the stiffer the geotextile gets. It seems that a part of the load is transferred via a reversed arch to the vertical wall in the upper part, which means the load is not only taken by the membrane but also partly conducted through the membrane to the wall.

3.3 *Conclusions of this section*

By means of the numerical simulation the hypothesis/conclusions from the interpretation of the centrifuge test results could be confirmed. Load redistribution due to arching and spreading is observed in the numerical simulation by comparing the vertical stresses in the embankment base for simulating the embankment as a vertical load and granular material.

4 CONCLUSIONS

Comparing the relation of embankment height and base width, which is 0.25 for the final embankment height, with the relation mentioned in the literature for the formation of a full arch (70% to 100% for an uniform thick layer), it becomes obvious that no full arch has developed within the embankment. However, the decrease of the vertical stresses within the consolidation phases can clearly be attributed to an arching mechanism probably enhanced by spreading forces.

For the safe system design, the decrease of the vertical pressure beneath the embankment axis is less important. The consideration of this effect would lead to a better prediction of settlement.

More important is the consideration of the load redistribution towards the vertical wall, since this leads to an increased load along the vertical wall, which does have a significant influence on the design for ULS as well as the SLS of the system.

There are still disagreement between measurement and numerical simulation, which may result from the ideal assumed boundary conditions, i.e. no friction at the side wall of the strong box on the axis of symmetry. The next step is to do the numerical simulation with more realistic values.

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