Analysis of an adaptive foundation system for embankments on soft soils by means of physical and numerical modelling

Analyse d'un système de fondation adaptatif pour les remblais sur sols compressibles par modélisation physique et numérique

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ABSTRACT: A new innovative foundation system for embankments on soft soil is currently being analyzed at the Ruhr-Universität Bochum, Germany, in cooperation with the company HUESKER Synthetic GmbH. The system consists of two parallel vertical walls (e.g. sheet pile walls), which are installed into the soft subsoil and connected at their top via a horizontal tension membrane (e.g. geotextile). The embankment is then constructed on top of this tension membrane. The aim of this research project is to demonstrate the applicability of the system and to develop an analytical calculation algorithm for serviceability and ultimate limit state of the system. To study the complex interactive system behaviour a strategy is followed using geotechnical centrifuge technology and numerical modelling. Measurement data from the centrifuge wall tests will be used for the validation and calibration of the numerical model.

RÉSUMÉ : Un système de fondation pour les remblais sur sol mou, innovant est actuellement analysé à l'université de la Ruhr à Bochum, Allemagne, en coopération avec l'entreprise HUESKER Synthetic GmbH. Le système consiste en deux palplanches verticales et parallèles, ancrées dans le sol mou et reliées par une membrane horizontale résistante à la traction. Le remblais est ensuite construit par-dessus cette membrane. Le but de ce projet de recherche est de démontrer la pertinence du système et de développer un algorithme analytique de calcul pour les états limites de service et ultimes. Pour étudier le comportement complexe du remblai, on comparera un modèle en centrifugeuse et une modélisation numérique. Les résultats des mesures des essais seront utilisés pour la validation et la calibration du modèle numérique.

KEYWORDS: soft soils, embankment, foundation system, geotextile, self-regulating, centrifuge tests, numerical modelling

1 INTRODUCTION

The construction of embankments on soft soils (e.g. for transportation, as break-waters or stockpiles) is a challenge due to their low shear strength, low permeability, high compressibility and high water content. The surcharge by the embankment can not only result in a local or total loss of stability (failure, see Figures 1 and 2) but also in unacceptable settlements or horizontal deformations, which could endanger structures nearby. The subsoil below the middle of the embankment will be loaded under approximately oedometric conditions, whereas the subsoil below the embankment shoulders will experience compressive as well as shear stresses.

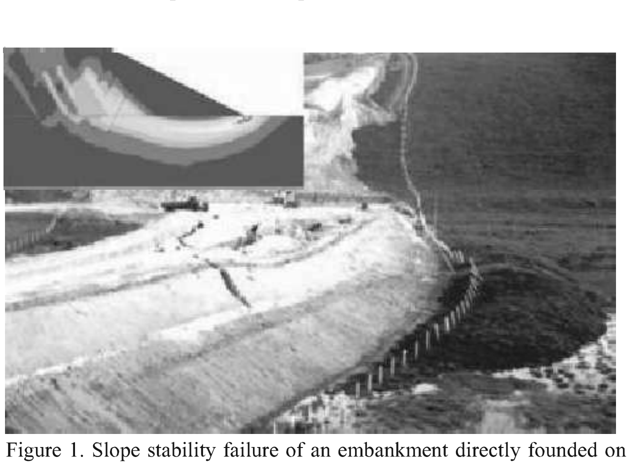

Figure 1. Slope stability failure of an embankment directly founded on soft soil and numerical illustrated shear failure zone (foto: HUESKER)

To overcome these issues different solutions such as a phased construction of the embankment with a basal reinforcement, prefabricated vertical drains and consolidation phases or the use of (geotextile encased) granular columns or rigid inclusions, e.g. prefabricated concrete piles, with a horizontal geotextile reinforcing layer, are available. Each system has its limitations however, which can be related to the thickness of the soft soil layer, height of the embankment, time and also economic, ecological or technical reasons.

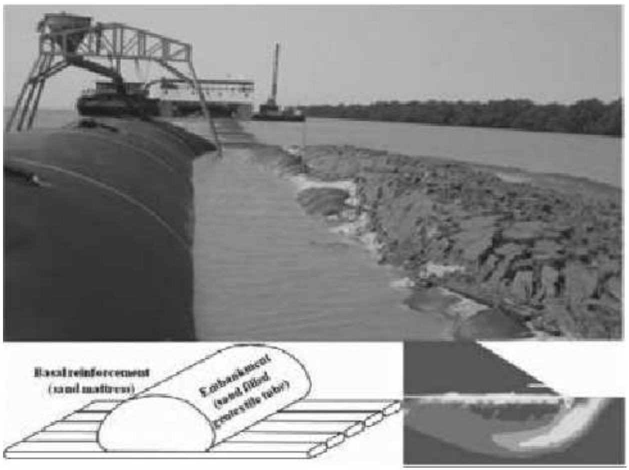

Figure 2. Soil extrusion below an embankment (sand filled geotextile tube) with basal reinforcement (sand mattress), system sketch and numerical illustrated shear failure zone (foto: HUESKER)

A new self-regulating foundation system for the construction of embankments on soft soils is presented in this paper, which is believed to be a more feasible and economical solution under certain boundary conditions. The new concept and its application areas are presented in the following sections.

2. NEW SELF-REGULATING FOUNDATION SYSTEM

2.1. *Description and basic ideas*

The new self-regulating foundation system consists of two vertical parallel walls (e.g. sheet pile walls) which are installed at a certain distance between each other into the soft soil and connected to each other by a horizontal tension membrane (e.g. geotextile). The tension membrane is assumed to cover the whole area in between the vertical walls. 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 membrane on top and the vertical elements (Figure 3).

The embankment will be constructed above the tension membrane, which is connected to the walls. This surcharge generates vertical and horizontal pressures and corresponding strains in the soft soil. The horizontal thrust tries to move the walls outwards. At the same time tension forces are mobilized in the tension membrane: first due to settlements (deflection) beneath the embankment and second due to the outward movements of the vertical walls tensioning the connected membrane additionally.

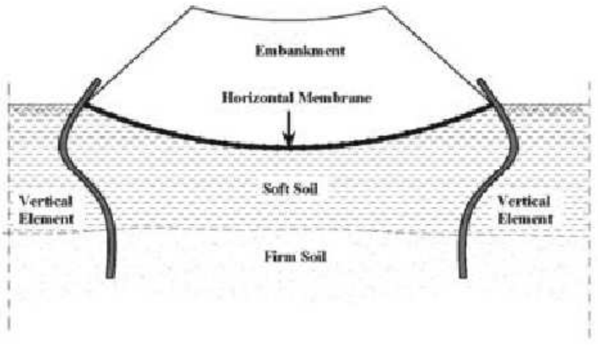

Figure 3. Sketch of deformed tension membrane foundation system

The basic ideas of the system are on the one hand to confine the soft soil by the vertical and horizontal elements to prevent excessive lateral deformation or even extrusion of the soft soil. This confinement results also in reduced vertical deformation. On the other hand a self-regulating mechanism of the system takes place. Each load increment provokes an increased horizontal pressure on the vertical walls and therefore a further outward deformation. This deformation results in a larger strain of the tension membrane and a corresponding higher tensile force. Thus the later provides an increased resistance to the outward displacement tendency of the walls. Say, the system reacts to a higher surcharge with a higher lateral restrain.

The foundation system not only ensures the global stability of the embankment but also “automatically” prevents or reduces deformations.

2.2. *Overview on related systems*

The use of a geotextile basal reinforcement is a well established and documented method for the construction of embankments on soft soils. Many authors have reported about research and cases studies, as e.g. Rowe and Li (2005). This will be the most economic solution, if there are no restrictions regarding the settlements, the horizontal “spreading”, the time for consolidation etc.

Wager and Holtz (1976) used in the 1960’s very short sheet pile walls connected via tie-rods to capture spreading forces of embankment on soft soils. The tie-rods and sheet pile walls acted like a basal reinforcement mechanism and were just placed at the base of the embankment, not being embedded into the soft ground. It is reported that several projects applied this method. This solution was not followed further when geotextile reinforcements became readily available, mainly for cost reasons.

Harata et al. (2008) reported about the use of sheet pile walls at the toe of embankments on soft soils to cut off the settlement depression. Due to the installation of the sheet pile walls into the ground a stress discontinuity between the embankment and the surrounding ground is generated, which leads to a reduction of the vertical deformation outside the embankment. In the design concept of Harata et al. only the equilibrium of the vertical forces is considered. Ochiai et al. (1991) studied in small scale laboratory tests different arrangements of two parallel sheet pile walls at the toes of the embankment, where the wall length and inclination were varied. Additionally in two of the tests the influence of a connection via tie-rods between the walls has been investigated. As a result of the tests the authors rated the different arrangements in respect of the deformation outside the embankment. The use of tie-rods led to decreased deformation. Design approaches have not been mentioned.

Adalier et al. (2003), Elgamal et al. (2002) and Tanaka et al. (2000) reported about the use of tie-rod connected sheet pile walls beneath embankments on loose, saturated sandy foundation soils to prevent earthquake-induced liquefaction. Adalier et al. (2003), analyzed the behaviour with centrifuge tests and Elgamal et al. (2002) performed numerical simulations based on these results. Tanaka et al. (2000) performed shaking table tests and numerical simulations. All researchers confirmed the benefit of tie-rod connected sheet pile walls beneath the embankment with respect to deformation or failure while earthquake-induced liquefaction occurs.

In both applications only single tie-rods are used, thus the embankment weight has to be carried only by the subsoil. A restraining tensile force as with the membrane foundation system is not generated by the embankment weight. Long time consolidation processes are not relevant in the case of the liquefaction issue and of little relevance where a stress discontinuity is of interest. Design approaches or system dependencies are not addressed.

Cofferdams do have a similar set-up but they are mainly constructed above the existing ground level. The infill is a well draining granular material, which provides the stability of the system. Cofferdams are mostly loaded horizontally from one side, so the construction sequence as well as the interaction between the structural elements and soil are completely different to above described foundation system for embankments on soft soils.

3. RESEARCH STRATEGY

3.1. *Aim of the research*

The aim of this research project is to demonstrate the applicability of the system, the self-regulation mechanism and to develop an analytical calculation algorithm for serviceability and ultimate limit state of the system.

3.2. *Theoretical system behaviour*

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 the interactions are time dependent. The stiffness of the soil as well as the total stress on the walls are changing with the consolidation from undrained conditions at the beginning of the embankment construction to drained conditions in the final state. The system behaviour depends on many factors e.g. the distance between the vertical walls, their length and degree of fixation, the weight of the embankment, the thickness, stiffness and shear strength of the soft soil, the stiffness of the vertical walls and tension membrane and the relation of the latter between each other.

A key factor for the design of the system is the knowledge of the earth pressure distribution along the sheet pile walls. This distribution is as mentioned before time and deformation dependent.

Due to the low permeability of mostly saturated soft soils the total surcharge load from the embankment during and directly after construction is carried by the pore water pressure. At this moment and under assumed oedometric conditions the additional horizontal pressure equals the vertical pressure from the surcharge, which represents the upper limit regarding the horizontal loading on the vertical elements. With progressing consolidation the additional horizontal pressure decreases until the effective horizontal earth pressure is acting, which represents a lower limit.

Since the self-regulating system is not infinitly rigid and the loading is not uniform but trapezoidal (Figure 3) the horizontal earth pressure will be in between these two limits at the very beginning and will decrease with time during consolidation.

Due to the deformation of the walls the earth pressure outside the walls will change from the at rest condition to passive earth pressure. Similarly inside the walls the earth pressure will change towards the active earth pressure. It has to be analyzed to which degree the passive and active earth pressure will be activated and how this is influenced by the length and bending stiffness of the vertical elements, the tensile stiffness of the membrane and the relation of the latter between each other. The above described behaviour leads to the conclusion that the maximum bending moment does occur immediately after the construction of the embankment when the total surcharge load from the embankment is carried by the pore water. This means the design of the vertical walls shall be done for undrained conditions.

The tensile forces in the tension membrane do also depend on time and deformation. Three different origins of tensile forces have to be considered (Figure 4).

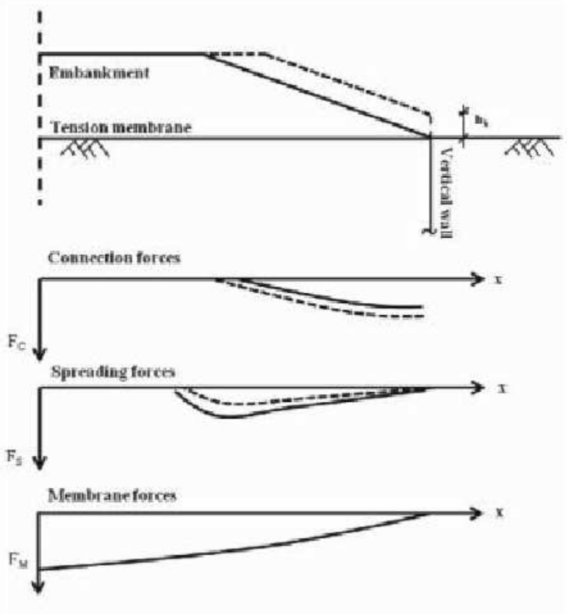

Figure 4: Acting forces in the tensile membrane (qualitative sketch)

Connection forces: Due to the outward movements of the vertical walls a tensile force is developed within the tension membrane.

Spreading forces: Due to the imbalance of the earth pressure in the region of the embankment shoulders spreading forces are generated. These spreading forces are mainly captured by the geotextile. In case of the installation of the sheet pile walls with an excess length (h_k> 0) above the ground level the spreading forces reduce but at the same time the connection forces increase.

Membrane forces: The settlements of the soft soil due to the embankment weight leads to a geometrical elongation of the tension membrane and therefore to tensile forces within the membrane.

For the tension membrane the connection force activated by the wall movements will be at its maximum during and immediately after construction of the embankment. The membrane force will increase during consolidation and reaches its maximum when consolidation comes to an end.

Possibly a further influence on the tensile forces is the heave which can occur in the region of the embankment shoulder when soil tends to squeeze out but is hindered by the walls and the membrane.

The different mechanisms are all interacting and increase or reduce the total tensile force in the membrane. Furthermore the creep of the tension membrane has to be taken into account, which will lead to reduced stresses in the membrane and may lead to some increased deformation.

3.3. *System analysis*

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 and calibration of the numerical model measurement data is required.

A real scale field test would generate the most reasonable data but boundary conditions are hard to control and consolidation takes a long time, which means the reproducibility of the tests would be very low. Small scale tests overcome these drawbacks, but they do not represent the realistic stress fields of the system. The centrifuge technique combines the advantage from field and small scale tests. Realistic stress fields can be generated, boundary conditions are well controlled and consolidation takes considerably less time due to the shorter drainage path. Due to these reasons the system is analyzed in the beam centrifuge Z1 at the Ruhr-Universität in Bochum, Germany (Jessberger and Güttler, 1988).

3.3.1. *Centrifuge tests*

By means of centrifuge tests the earth pressure distribution under varying relations between the bending stiffness of the vertical walls and the tensile stiffness of the horizontal membrane will be analyzed.

Therefore the vertical model walls are instrumented with strain gauges and measurements are taken frequently during the staged construction of the embankment and consolidation phases. The measurement data can be transferred into bending moments by conversion factors. The total earth pressure distribution can then be determined by derivation of the bending moment distribution.

A detailed description of the centrifuge test set-up and execution can be found in Detert et al. (2012). The results of the centrifuge tests are analyzed and used for the validation and calibration of the numerical model.

3.3.2. *Numerical parameter study*

Numerical methods are a powerful tool in analyzing complex mechanism with varying parameters. The right choice of the soil model is very important for the numerical simulation. The soil model has to be capable of reproducing the significant soil mechanical processes occurring in the system as well as the load history of the construction steps and the centrifuge test procedure. The data obtained from the centrifuge tests can be used to confirm the choice of the right soil model.

From the centrifuge test a resultant earth pressure (sum of passive and active pressure) distribution is obtained. By means of numerical simulations it is possible to distinguish between the different time dependent earth pressure components out- and inside the system, as well as the pressure from the embankment weight. It is also possible to identify and observe the different origins of the tensile forces in the membrane.

With the numerical parametric study the sensitivity of different parameters and their impact on the stress and strain of the different system components can be analyzed.

Based on the results of the numerical investigations an analytical design approach will be developed.

4. CONSTRUCTION ASPECTS

For the system construction well established techniques such as sheet pile wall installation can be used and the appropriate machinery is generally available worldwide. Site preparation for the equipment is reduced to two lateral “construction roads” for the installation of only the vertical wall elements, compared to full width working platforms which are required in the case of conventional soil improvement techniques such as e.g. vibro stone columns. The soft soil becomes part of the system and no soil disposal is necessary. Less fill material is required to reach the final height of the embankment due to the reduced settlement and lateral deformation.

Depending on the soft soil conditions and/or the lifetime of the embankment it is possible to reclaim the vertical elements with little effort. It is also possible to have a partly open wall system by installing shorter sheet piles in-between.

From the practical point of few a key element of the system will be the connection of the geotextile and the vertical elements. Large forces are to be transferred between the tension membrane and the vertical walls.

The use of geogrids as an anchor element has already been applied several times as shown in Detert et al. (2008). Different case studies demonstrate the applicability and the good performance of geogrid anchors for sheet pile walls or similar.

A possible connection detail is shown in figure 5. The connection consists here of u-shaped steel rings welded onto the sheet pile wall and a steel pipe pushed through these rings.

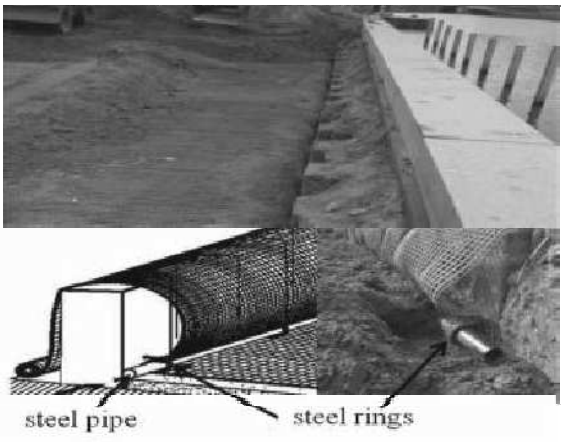

Figure 5. Connection detail between sheet pile wall and geogrid anchor

The geogrid is wrapped around this steel pipe and the upper end anchored back into the embankment. Also more flexible connections are possible if large settlements are expected.

5. CONCLUSION

The paper describes the theoretical behaviour of a new foundation system for embankments on soft soils. The system consists of two parallel vertical walls, which are installed into the soft subsoil and connected via a horizontal tension membrane. The embankment is constructed on top of this membrane. It was found that the understanding of the earth pressure distribution along the walls, which is time and deformation dependent, is a key factor for the design. Due to the complex interaction between the system components a strategy was developed to analyze the system. Numerical simulations offer a very efficient method to perform comprehensive parametric studies for analyzing the impact on the system behaviour of the different system components. For the validation and calibration of the numerical model measurement data from the system behaviour is required. It was concluded that centrifuge tests are the most beneficial technique for gaining this required data.

From a practical point of view it was found that the installation of the system is not difficult. A key factor is the connection of the tension membrane to the vertical walls, which has been previously realized in different applications.

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