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An Innovative Self-Regulating Membrane Foundation System for Embankment Construction on Very Soft Soils

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ABSTRACT: This paper describes a new, self-regulating, interactive membrane foundation system for the construction of embankments on very soft soils. The system could be used in tailing dams, where filter-pressed tailings could be stored on top of hydraulically placed tailings. Due to the low shear strength, high compressibility and water content, the already placed tailings may not be strong enough to bear the load from the new placed filter-pressed tailings pile. As a result bearing failures or excessive deformation may occur. In the paper the system itself as well as the analysis of its load bearing and deformation behavior and its possible application to the mine tailings are described and discussed. Beside its easy installation, a further economic advantage of the system in its application in tailings is the possibility to reuse parts of the system in the progress of placing the filter-pressed tailings.

1 INTRODUCTION

1.1 *Current situation*

There are many mines where the tailings facility has been formed by hydraulic fill placement of the tailings. These tailings may still be wet, soft and weak. Space limitations and the desire to convert from hydraulic fill tailings placement to filter-pressed tailings placement, may economically be done by placing the filter-pressed tailings pile on top of the old hydraulic fill tailings.

The construction of new tailings piles, access berms, dykes or perimeter embankments on very soft soils, e.g. peat, clay or tailings, is a challenge due to their low shear strength, low permeability, high compressibility and high water content.

The surcharge load imposed by the pile may result in a local or total loss of stability of the foundation and hence of the new pile. In addition, unacceptable settlement and horizontal thrust as well as deformation may occur in the soft subsoils.

Typical bearing failure mechanisms of embankments or stockpiles on soft subsoils are rotational ground and slope failure (see Figure 1) or the extrusion of the soft subsoil beneath the imposed load due to the embankment.

While the additional vertical loads are carried by the increased pore water pressure (generation of excess pore water pressure), the additional shear forces beneath the embankment slopes, which result from the spreading forces in the slope as well as unbalanced horizontal forces in the subsoil, are critical in regard to the pile stability. These shear forces have to be resisted by the shear strength of the subsoil (water cannot take any shear forces). Due to the low permeability of fine-grained soils, excess pore water pressure and shear stresses in the subsoil are increased by the additional loads. Conversely the effective stresses, which control the shear strength of the subsoil, are unaffected or do not increase immediately. Therefore bearing failure as described above may occur during the filling process.

Figure 1: Typical rotational bearing failure for embankments on soft soils

1.2 *Known construction methods and foundation systems*

Different methods are known to construct embankments on very soft soils to overcome these failure mechanisms. If the subsoil does have some shear strength, subsoil extrusion will not occur, and the stability can be increased by slow stepwise construction of the embankment with intermediate consolidation phases. Faster construction is possible with the application of basal geosynthetic reinforcement layers; these layers capture the spreading forces, which do occur in the embankment slopes, and prevent excessive shear stresses in the subsoil. To increase the consolidation rate of the subsoils and the development of shear strength in the subsoil, wick drains can be used in combination with the basal reinforcement.

If the subsoil is even weaker, the installation of load bearing elements such as granular columns or concrete piles may be required. These elements capture the load from the embankment and transfer it through the weak subsoil into an underlying competent layer. For unbounded granular columns an additional lateral support in terms of a geotextile encasement might be required to prevent excessive lateral deformation or even bulging of the columns due to insufficient horizontal counter pressure from the subsoil.

Each of the mentioned methods has its limitations, which relate to the thickness of the soft soil layer, height of the pile, rate of the pile construction and cost constraints.

The self-regulating interactive membrane foundation, which is described in the next section, might be a valuable addition to the existing methods for applications in tailings, especially due to the fact that the total footprint area of the embankment does not have to be accessible for the installation equipment and the possible reuse of system parts in the progress of storing the tailings.

1.3 *Self-regulating interactive membrane foundation*

The self-regulating interactive membrane foundation system consists of two vertical and parallel walls (e.g. sheet pile walls) which are installed at a certain distance between each other into the soft soil and are 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 vertical and horizontal elements.

The embankment is constructed above the tension membrane. Parts of the load will be captured by the membrane and transferred directly into the vertical walls. The remaining load of the embankment generates horizontal pressures onto the vertical walls which provoke outward movements. At the same time tension forces are mobilized within the tension membrane due to settlement depression beneath the embankment and outward movements of the vertical walls, which counteract these movements and therefore limit the horizontal deformation (see Figure 2).

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, which results in reduced vertical deformation. On the other hand, the self-regulating mechanism of the system, where each load increment provokes an increased pressure on the vertical walls and therefore a further outward deformation results in a larger strain of the tension membrane and consequently a higher restraining anchor force to counteract the outward movements.

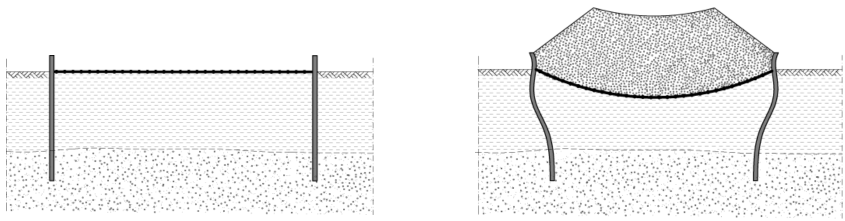


Figure 2: Not deformed and unloaded system (left); deformed and loaded system (right)

Thus the foundation system ensures the global stability of the embankment and prevents or reduces deformations and horizontal thrust in the subsoil.

The load bearing and deformation behavior depends on various parameters. To investigate the complex system behavior, comprehensive centrifuge model tests and numerical investigation have been executed.

2 LOAD BEARING AND DEFORMATION BEHAVIOR

2.1 *Physical and numerical analysis of the system*

For a sound design of the system, it is important to know and understand the stress and strain evolution over time. Due to the complex and time dependent interaction and the multitude of influencing parameters, a comprehensive numerical parametric study has been conducted 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 principal configurations of the system were analyzed, before the systematic investigation by numerical simulations started.

2.1.1 *Centrifuge model tests*

The centrifuge models tests were done in the beam centrifuge of the Department of Foundation Engineering, Soil and Rock Mechanics, at the Ruhr-Universität Bochum in Germany. A detailed description of the beam centrifuge can be found in Jessberger & Güttler (1988).

The tests were done on a model which represents an embankment of 10 m height founded on 10 m thick soft soil layer. The model was produced at a scale of 1:50 and consequently accelerated in the centrifuge to 50g. The stress field in the centrifuge model is therefore equivalent to the stress field of the real scale system set-up (prototype) due to the elevated acceleration field of 50g. This is important to reproduce the correct stress-dependent behavior of the soils. The structural elements, such as sheet pile walls and tension membrane, were scaled according to validated scaling laws.

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.

The centrifuge models were extensively instrumented to measure stresses, pore water pressure, deformations and bending moments of the sheet pile wall. A detailed description of the centrifuge test set-up and execution can be found in Detert et al (2014). The model dimensions are shown in Figure 3.

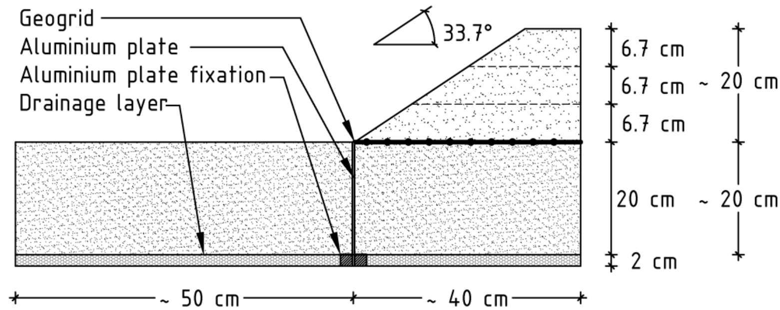


Figure 3: Centrifuge model dimensions

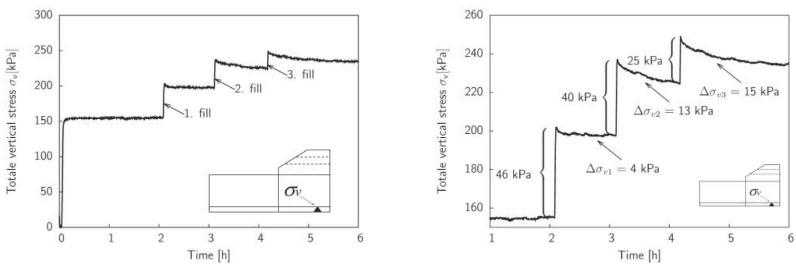
2.1.2 *Numerical simulations*

The numerical simulations have been executed with the program Plaxis 2D. In the first step the numerical model was validated based on the results of the centrifuge model tests. With the validated numerical model, the stresses and strains within the system could be investigated and the load bearing behavior analyzed. The dominating parameter on the system behavior was determined by global sensitivity analyses; their quantitative influence on the system behavior was evaluated subsequently by parametric studies and are represented in design charts.

2.2 *Results*

2.2.1 *Arching mechanism in the embankment body*

In Figure 4a, the total vertical pressure over time measured in the consolidation layer beneath the soft subsoil and embankment can be seen. The three construction phases of the embankment are clearly shown by the strong increase of the total vertical pressure. During the consolidation phases, a decrease of the total vertical pressure over time is observed (see Figure 4b).



4a 4b

Figure 4. Total vertical pressure over time measured in the consolidation layer below the soft subsoil and the embankment over time.

While in the first consolidation phase, the decrease of the total vertical pressure is only 4 kPa; a much stronger decrease can be observed in the second and third consolidation phase. The evaluation of all executed centrifuge model tests shows a clear relation between the embankment height and the decrease of the total vertical pressure (see Figure 5).

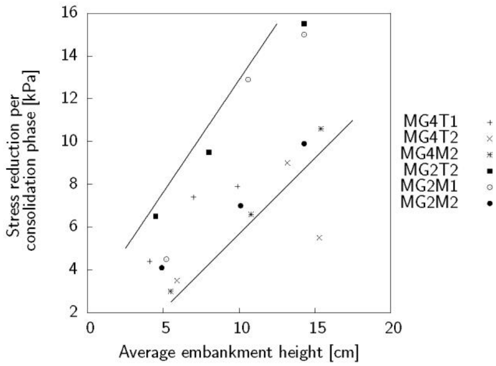


Figure 5. Decrease of total vertical pressure over average embankment height

At the same time, an increasing outward movement of the wall is observed during the consolidation phases, although the excess pore water pressure, and therefore the pressure on the vertical walls, does decrease (Figure 6).

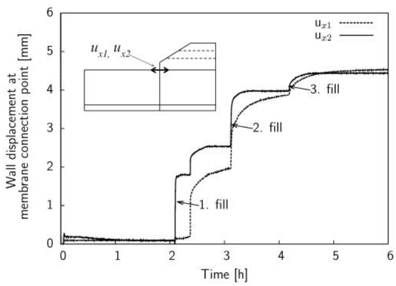
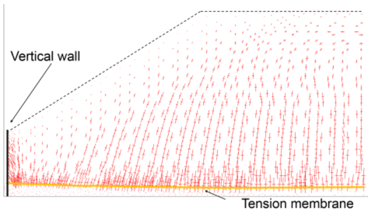


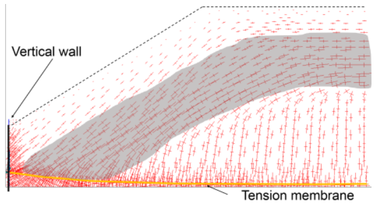
Figure 6. Horizontal wall displacement over time measured at the connection point of the tension membrane to the vertical wall (positive values represent an outward movement)

By means of the numerical simulations, the principal stresses in the embankment body before and after consolidation can be analyzed. As shown in Figure 7a, immediately after the construction phase of the embankment, the principal stresses are nearly vertical and horizontal. In the embankment slope a minor rotation occurs due to spreading forces. After consolidation a clear rotation of the principal stresses in the embankment body can be seen in Figure 7b. The rotation of the principal stresses occur due to a load transfer from the middle of the embankment towards the embankment slopes. Due to the settlement of the embankment during the consolidation phase, the friction between the soil particles in the embankment body is mobilized and an arching mechanism develops.

A more detailed analysis of this mechanism shows that the load redistribution stabilizes the system, since a rotational failure mechanism in the subsoil (see Figure 8), which develops in the transition zone between embankment slope and crest towards the vertical wall at the slope toe, is retained by the arch. The zone where this rotational failure comes “up” is the zone where the load transfer arch props on to the subsoil. Due to the beginning rotational failure, the subsoil “presses” into the embankment and creates a zone of higher stiffness, which in turn attracts the load from the load transfer mechanism.



7a. Before consolidation



7b. After consolidation

Figure 7. Principal stresses within the embankment body before and after consolidation.

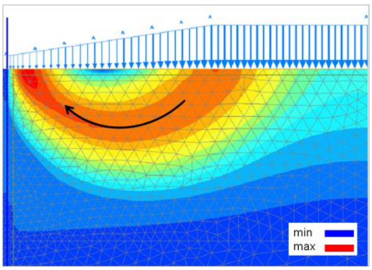


Figure 8. Total displacement in the subsoil, which occurs when arching in the embankment is prevented by simulating the embankment as vertical load instead of a frictional material.

2.2.2 *Dominating system parameter*

By means of global sensitivity analysis and parametric studies, the dominating system parameters and their quantitative influence on the loading onto the system components have been determined.

Within a global sensitivity analysis, the main system parameters, which are believed to have the biggest influence on the system behavior, are varied in parallel in multiple numerical simulations and their influence on selected system responses are evaluated. With this kind of analyses it is certain that the interdependent influence of the single parameters on the system behavior is captured.

The identified dominating system parameters are:

- Tensile stiffness of the membrane
- Subsoil stiffness
- Weight of the embankment material
- Height of the sheet pile wall extension above ground level
- Height of the embankment
- Relation between height and width

The bending stiffness of the sheet pile wall does not have a significant influence on the system behavior.

2.2.3 *Design situations*

The highest stresses within the sheet pile walls are developed immediately after the embankment construction when the excess pore water pressure is acting as a load on the sheet pile walls. The highest loading of the tension membrane occurs after consolidation, when the load transfer mechanism is fully developed and the settlement depression has reached its final magnitude.

3 POSSIBLE APPLICATION TO TAILINGS DAMS

Nowadays the storage of filter-pressed tailings in existing ponds filled by hydraulic placement of tailings is being considered for many mines.

The bearing capacity of the existing tailings in the ponds is mostly very low and the placement of filter-pressed tailings will result in bearing failures. Furthermore the horizontal pressure on the existing perimeter embankments will increase due to the additional load and may endanger their stability.

To overcome issues with the bearing capacity of the existing tailings and the horizontal pressure on the perimeter embankment, the self-regulating and interactive membrane foundation (SIM) can be used. As described above, it assures the stability of the embankment and reduces the horizontal thrust in the subsoil outside of the system.

Due to the dimensions of a tailings pond, the multiple use of the single SIM “cells” as a foundation system is possible. The installation process starts at either side of the pond by installing a vertical wall, e.g. sheet pile wall, into the perimeter embankment of the pond. The second vertical wall will be installed at a certain distance. The distance between the sheet pile walls depends on different boundary conditions, which could be deformation requirements, depth and shear strength of the existing soft subsoil and allowable horizontal thrust in the subsoil. The greater the horizontal distance between the vertical walls, the “softer” the system behavior; the horizontal and vertical deformations will increase.

After installation of the two walls, the tension membrane will be installed and the placement of the filter-pressed tailings starts. Once the storage capacity is reached, a further vertical wall is installed and connected to the outer wall of the first “SIM cell”. In-between these walls a further tension membrane is installed and connected to the walls. Those steps are repeated in the progress of filling the tailings. The construction process is shown in Figure 9.

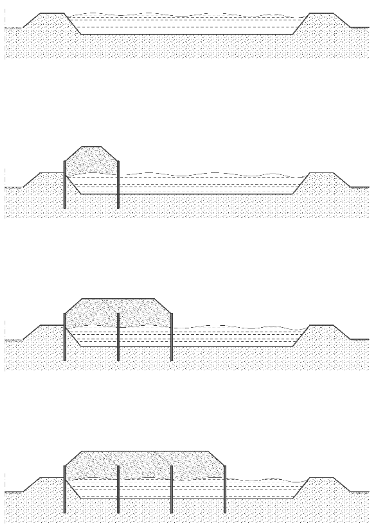


Figure 9. Schematic construction process to store material by the use of the SIM foundation system on soft and weak existing tailings

At a certain time, when enough stability on either side of a “cell” is provided by further “cells” or the subsoil has developed sufficient shear strength to withstand bearing failures or excessive deformations, parts or even all of the elements of the vertical wall can be extracted and used again for the construction of additional “SIM cells” in the progress of the filling operations (see Figure 10). This offers an economical advantage of the SIM system over existing foundation systems. The outermost one or two "cells" should be kept for stability reasons.

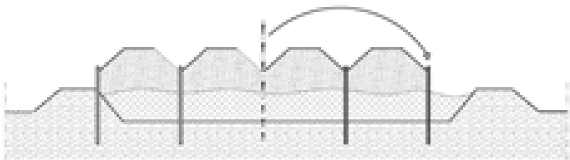


Figure 10. Reuse of the sheet pile wall in the progress of filling operations

Furthermore, the SIM could be used to create an access road into the pond or to create a separation dam within the pond.

3.1 *System modification*

The lengths of the vertical wall can be varied (Figure 11). For the above described and analyzed system, an embedment of the vertical walls in a competent bearing layer was presumed. All shorter length of the vertical walls are possible, so that they reach down to the bottom of the subsoil or even end within the subsoil layer. The load bearing behavior of the system will change if the vertical elements are not embedded within a competent layer and horizontal as well vertical deformation will increase. Nevertheless, where deformations in a certain range are not critical, the use of shorter sheet piles might be an interesting option.

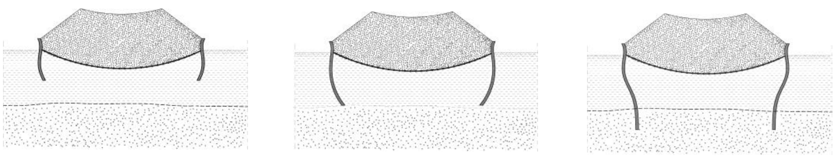


Figure 11. Possible system modifications with shorter sheet pile walls

3.2 *Connection of the tension membrane to the walls*

Due to its flexibility, the connection between the sheet pile wall and the tension membrane can be made quite simply. The connection can consist of u-shaped steel rings welded or bolted to the sheet pile wall. The tension membrane is placed close to the sheet pile wall and a steel pipe is pushed through the rings (see Figure 12), before the tension membrane is folded back. Similar techniques have been described by Detert (2008).

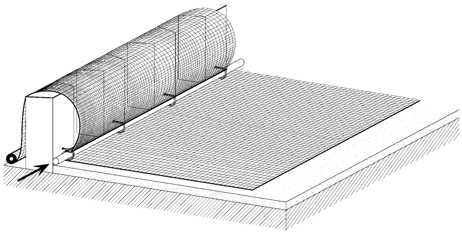


Figure 12. Connection of the tension membrane to the sheet pile walls

4 CONCLUSION

The paper presents a new foundation system for embankment construction or stockpiling on very soft sub grounds. The self-regulating membrane foundation system is described and results from comprehensive centrifuge model tests and numerical analyses of the load bearing behavior and dominating system parameters are presented.

A possible application within tailings ponds is presented and discussed. The easy installation and the possibility of reusing system elements makes the self-regulating interactive membrane solution an interesting option to increase the storage capacity of existing ponds filled with very weak tailings.

Modification of the system is briefly discussed and the connection detail between tension membrane and sheet pile wall has been shown.

5 REFERENCES

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