Design approach for the self-regulating interactive membrane foundation system for embankment construction on very soft soils

Oliver Detert
HUESKER Synthetic GmbH, Germany

Diethard König
Ruhr-Universität Bochum, Germany

Dimiter Alexiew
Consultant Geosynthetics & Geotechnics, Germany

ABSTRACT: The paper deals with an innovative foundation system for embankments on soft soils. It consists of two sheet pile walls, which are installed parallel to each other, to confine the soft foundation soil. Those sheet pile walls are firmly connected on the ground level by a geotextile with high tensile stiffness. The embankment will be constructed on top of the geotextile, which will act as a tension membrane. The complex interactive load bearing behavior has been analyzed by means of centrifuge model tests and numerical analyses. Based on those investigations a semi analytical design approach has been developed. The paper describes the system set-up, the centrifuge model tests, the numerical analyses, the load bearing behavior, the design approach and possible application areas.

Keywords: Self-regulating interactive membrane foundation, soft soils, centrifuge model tests, numerical analyses, design approach

1 INTRODUCTION

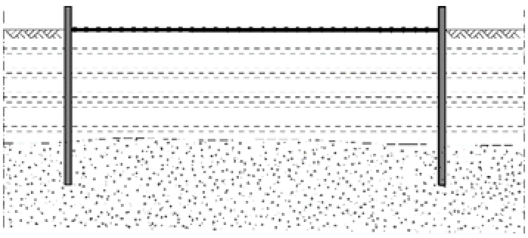
The construction of embankments on very soft soils e.g. for transportation, breakwaters, stockpiles or access roads into swamps or sludge lagoons, is a challenge due to the low shear strength, low permeability, high compressibility and high water content of the soft subsoils. The surcharge load imposed 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 in the subsoil, which could endanger nearby structures. To overcome these problems, different construction methods are applicable.

The choice of the right method does depend on different boundary conditions, which are related to technical, economical and ecological requirements. Especially technical requirements are often dominating the choice. Technical requirements can be related to the performance of the structures as well as to the required construction equipment.

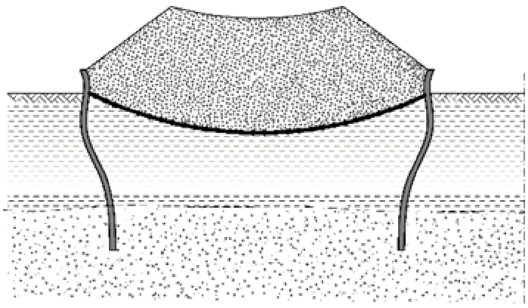
Based on a project inquiry with very limited access to advanced construction equipment, respectively techniques, the self-regulating interactive membrane foundation has been developed. The main focus was to be able to construct a foundation system with nearly worldwide accessible equipment and materials.

The self-regulating interactive membrane 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 of high tensile stiffness which acts as a tension membrane (Figure 1a). The embankment is constructed on its top (Figure 1b). The embankment load generates a significant horizontal soft soil pressure onto the vertical walls resulting in outward movements and bending. These movements are progressively restricted by the tension membrane ("self-regulation"). The system ensures global stability, controls settlements and horizontal deformation and reduces the impact on the walls. .

The complex interactive system behaviour has been comprehensively analysed by centrifuge model tests and numerical simulations. A design approach considering this complex interactive behaviour of the system has been developed based on those research results. The paper describes the system set-up, the centrifuge model tests, the numerical analyses, the load bearing behavior, the design approach and possible application areas.



a)



b)

Figure 1. System as installed (a); loaded and deformed system (b)

2 PHYSICAL AND NUMERICAL ANALYSIS OT THE LOAD BEARING AND DEFORMATION BEHAVIOR

2.1 *Introduction*

The understanding of the stress and strain evolution in the system over the loading and time period is critical for a sound design. Due to the complex and time dependent interaction behavior and the multitude of influencing parameters, a comprehensive numerical parametric study has been conducted for the system analysis. For the validation of the numerical simulation, measurement data are required to demonstrate the capability of the numerical simulation 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 a systematic investigation by numerical simulations started.

2.2 *Centrifuge model tests*

The geotechnical beam centrifuge of the department of foundation engineering, soil and rock mechanics at the Ruhr-Universität Bochum in Germany has been used to conduct the centrifuge model tests. A detailed description of the beam centrifuge can be found in Jessberger & Güttler (1988). By means of the centrifuge a small scale model can be analyzed in the real stress field of the system prototype. This is most important to reproduce the real stress-strain depending behavior of soils.

The tests were done on a model which represents an embankment of 10 m height founded on a 10 m thick soft soil layer. The model was constructed at a scale of 1:50 and consequently accelerated in the centrifuge to 50g. Due to the elevated acceleration field of 50g the stress field in the centrifuge model is equivalent to the stress field of the real scale system set-up (prototype). Structural elements, such as sheet pile walls and tension membrane, were scaled according to validated scaling laws (Jessberger (1992), Springman et al. (1992), Schürman (1997), Viswanadham and König (2004), Garnier and Gaudin (2007)).

The soft soil has been generated from slurry, which has been consolidated in the centrifuge at 50g. Then the embankment was constructed in three stages by means of an in-flight refillable and moveable sand hopper. Each construction stage was followed by a consolidation phase of about 1 hour. In the centrifuge model tests only a half of the system was installed due to its symmetry.

During the tests the stresses, pore water pressure, deformations and bending moments of the sheet pile walls have been measured by comprehensive measurement program. A detailed description of the centrifuge test set-up and execution can be found in Detert et al. (2012). Figure 2 shows the centrifuge test set-up in model simulation.

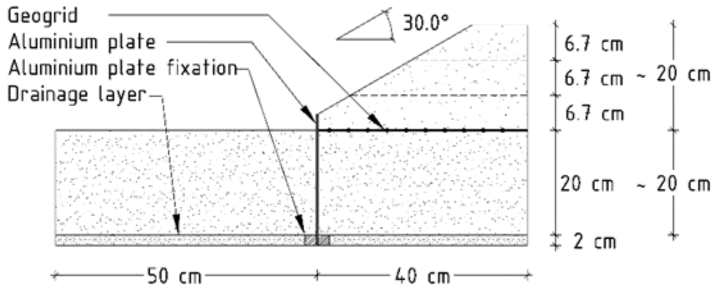


Figure 2. Centrifuge model (model dimensions)

Figure 3. shows the in-flight construction of the embankment in three steps in the centrifuge.

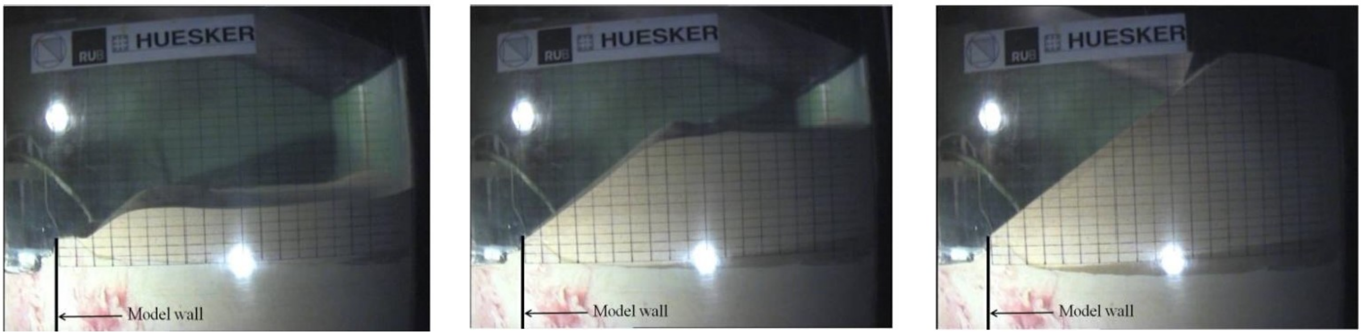


Figure 3. Construction steps of the embankment in-flight in the centrifuge

2.3 *Numerical simulations*

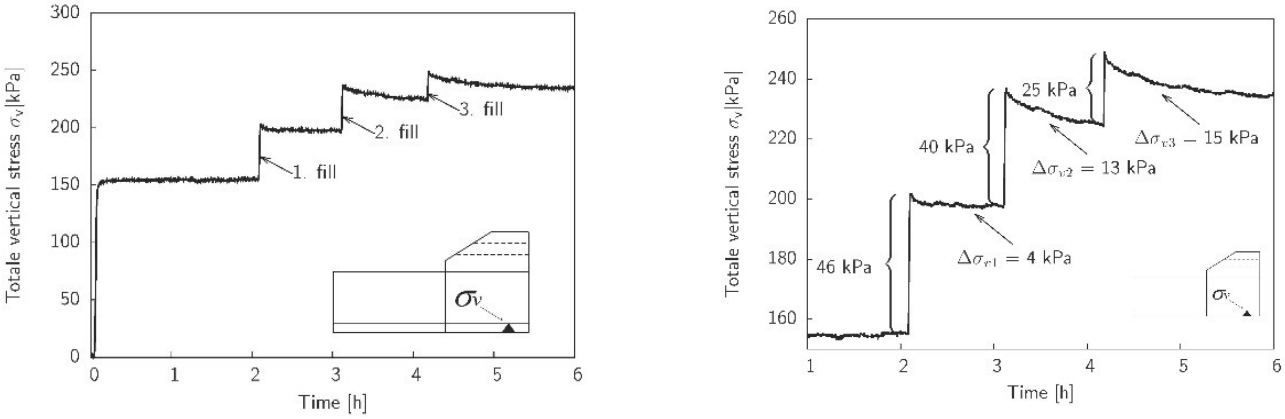
The numerical simulations have been executed with the program Plaxis 2D 2012 (Brinkgreve et. al.). In the first step the numerical model was validated based on the results of the centrifuge model tests. With the validated numerical model, the stresses and strains within the system could be investigated and the load bearing behavior analyzed. The dominating parameters of the system behavior have been determined by global sensitivity analyses; their quantitative influence on the system behavior was evaluated subsequently by parametric studies and can be represented in design charts (Detert, 2016).

2.4 *Results*

2.4.1 *Arching mechanism in the embankment body*

The results of the centrifuge model tests are presented in model dimensions. In Figure 4a, the total vertical pressure over time measured in the drainage layer at the bottom of the model (Figure 2) 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 $\Delta\sigma_V$ as indicated in Figure 4b over time is observed.

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 (Figure 5). 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).



a) b)

Figure 4. Total vertical pressure over time measured in the drainage layer at the bottom of the model over time for the full range (a) and zoomed in to analyze the different load steps (b).

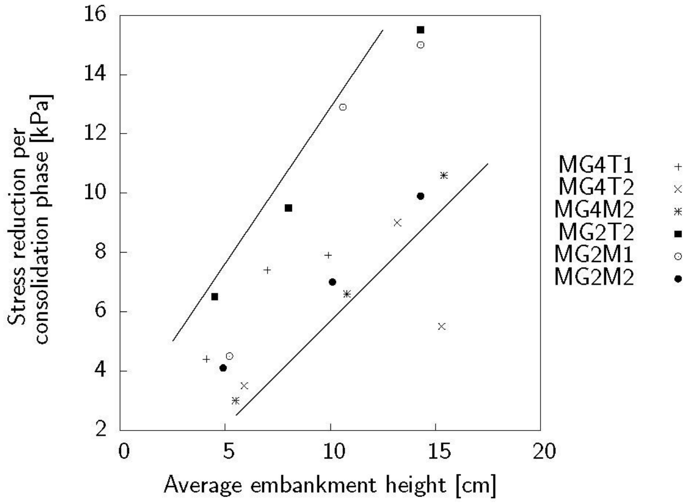


Figure 5. Decrease of total vertical pressure over average embankment height (results of different combinations of tensile stiffness of the geotextile and thickness of model wall; MG = Membrane Foundation; 4 = 4 mm and 2 = 2 mm model wall thickness; T = Geogrid Polyester, M = Geogrid Polyvinylalcohol, last number either test no. 1 or test no. 2).

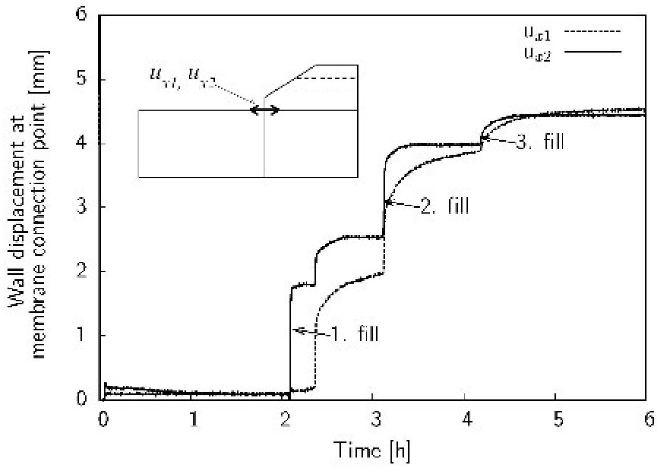
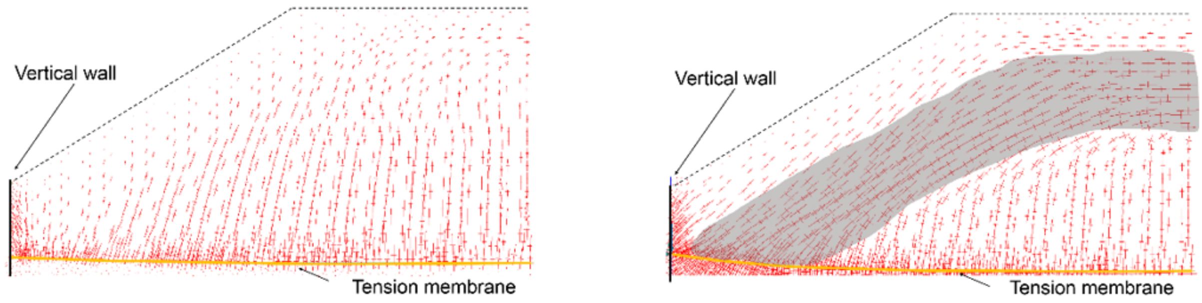


Figure 6. Horizontal wall displacement over time measured at the connection point of the tension membrane to the vertical wall (positive values represent an outward movement).

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 (Figure 7b) due to a load transfer from the middle of the embankment towards the embankment slopes (arching mechanism). 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) b)

Figure 7. Principal stresses within the embankment body before (a) and after consolidation (b).

A more detailed analysis of this mechanism shows that the load redistribution stabilizes the system, since a rotational failure mechanism in the subsoil (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.

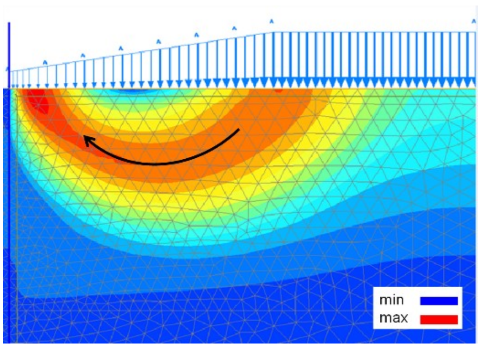


Figure 8. Rotational movement (most probable failure mechanism) within the soft soil beneath the embankment.

3 DESIGN APPROACH

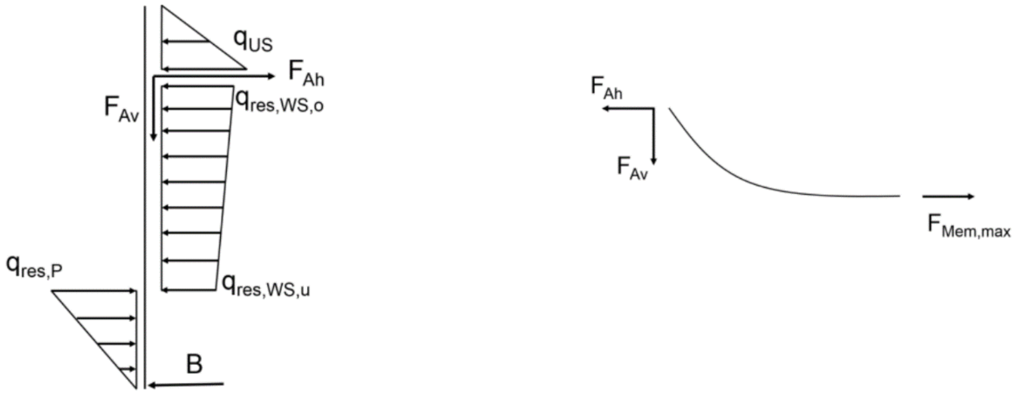
3.1 *Concept*

The conducted investigations have shown that two main loading conditions do occur within the system.

The maximum loading onto the sheet pile walls occur directly after the placement of the embankment material. At this stage the whole weight of the additional material is carried by the pore water pressure, so that excessive pore water pressure is generated. This excess pore water pressure is acting onto the walls.

During the consolidation phase the excess pore water pressure decreases and the embankment load is carried by the subsoil. This leads to a reduction of the pressure onto the sheet pile walls. At the same time the embankment settles and additional tensile forces in the membrane are activated. Due to the observed arching mechanism in the embankment body (see Figure 7) and the rotational movement of the soft subsoil beneath the slope of the embankment the loading of the sheet pile wall in the upper zone increases.

Based on this observation there two main design situations: directly after embankment placement and after the consolidation phase. For design purposes the system is split into two subsystems (Figure 9). Subsystem 1 is to calculate the stresses and deformation of the sheet pile wall and subsystem 2 to calculate the maximum tensile force of the tension membrane as well as the connection forces of the tension membrane to sheet pile wall. The last force is the connection between the two subsystems.



Subsystem 1) Subsystem 2)

Figure 9. The system is split into two subsystems for design purpose. (q_{us} = resulting loading on the sheet wall protrusion; F_{av} / F_{ah} = vertical and horizontal connection forces of the tension membrane; $q_{res,WS,o}$ / $q_{res,WS,u}$ = resulting loading on the sheer wall within the soft soil layer at the top and bottom; $q_{res,P}$ = esulting loading on the sheet pile wall within in the firm foundation layer; B = substitution force)

3.2 *Factors*

Within the numerical investigations a global sensitivity analyses has be conducted to determine the parameters of the system dominating the load-bearing behavior. Those parameters are

- Embankment height and weight
- Length of the sheet pile wall extension above ground (protrusion)
- Tensile modulus of the tension membrane
- Soft soil stiffness
- Bending stiffness of the sheet pile wall

The maximum stresses and tensile forces have been observed for a ratio between embankment height and base width of 0.25. Based on comprehensive numerical parameter studies design charts have been developed to determine the membrane forces as well as the acting forces on the sheet pile wall (Detert 2016). The design charts are based on nine standard configurations of the system. Adaption factors can be derived from the design charts for further configuration within a certain range to determine the loads on the sheet pile wall or the forces in the membrane.

The tensile force is derived as follows:

$$F_i = F_{0.25,i} * A_{geo,i} * A_{\gamma,i} * A_{E\_oed,i} * A_{J,i}$$

Where as

F Tensile force in the membrane
i vertical, horizontal connection force or maximum tensile force
$F_{0.25}$ Tensile force of standard configuration (ratio embankment height to base width of 0.25)
A_{geo} Adaption factor for deviating geometries
A_{γ} Adaption factor for densities of the embankment fill material greater 17 kN/m³
A_{E_oed} Adaption factor for soft soil stiffness smaller 3000 kN/m²
A_j Adaption factor for tensile moduli of the tension membrane smaller than 50.000 kN/m

The determination of the other loadings onto the sheet pile wall follows an analogue procedure. Those diagrams have been developed for undrained and drained conditions, which allow checking the both cases. Whereas the force in the membrane can be directly determined by the use of the design charts, a calculation has to be carried out, to calculate the stresses in the sheet pile wall.

3.3 *Example*

Figure 10 shows a system which has been calculated based on the design charts and with numerical methods. The configuration of this system has not been used before to derive the design charts. Table 1 shows the deviation between the both design approaches.

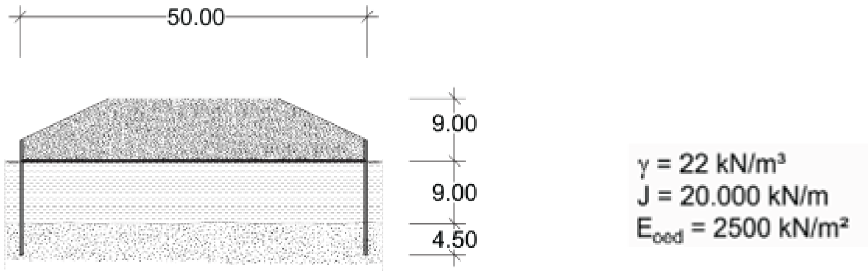


Figure 10. System configuration for comparative calculation between the developed approach using the design charts and numerical methods (γ = unit weight embankment, J = tensile stiffness membrane, E_{oed} = oedometric modulus soft soil)

Table 1: Deviation of calculation results using design charts and numerical methods before and after consolidation

F_{ah} [kN/m]		F_{max} [kN/m]		M_{field} [kN/m	
before	after	before	after	before	after
8%	7%	3%	0%	8%	12%

Figure 11 shows the bending moment over the height of the sheet pile calculated with both methods.

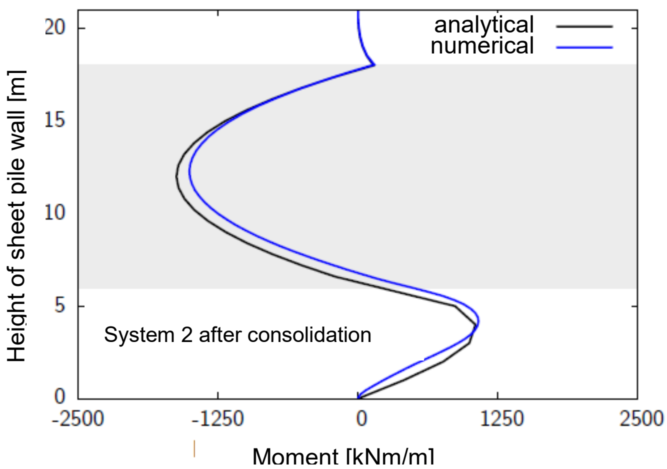


Figure 11. Bending moment of the sheet pile wall over the height. The grey area marks the soft soil layer.

The results of table 1 comparing the forces as well as the comparison of the bending moments in Figure 10 demonstrate a good agreement between the calculation methods.

4 POSSIBLE APPLICATION AREAS

As mentioned above, the system was developed to allow for easy construction technologies of embankments on soft soils, which are worldwide accessible. Whereas the horizontal deformation ("spreading") can to some extend be controlled by the choice of the geotextile tensile stiffness, there is less influence on the vertical deformations (settlements).

Some possible application areas are therefore:
- Stockpiles, where settlements are not critical
- Dykes, where settlements can be compensated by extra material to reach the required height
- (Temporary) access roads in very soft soils, such as tailings or sludge lagoons (further advantage: the sheet pile walls can be recovered after usage)
- General embankments, where the total settlements are less relevant, as long as relative settlements stay in a certain range

5 CONCLUSION

The complex load bearing behavior has been analyzed by means of sophisticated centrifuge model tests and comprehensive numerical studies. The results of the model tests helped to understand the principal system behavior and to validate the numerical simulations. Based on the conducted tests and simulations an analytical design approach, including design charts, has been developed. The comparison of the results between the developed design approach and numerical simulation has shown a very good agreement.

The system allows for an easy and fast construction of embankments on very soft soils. It is one option more to be considered in such cases. Depending on the deformation requirements different application areas have been mentioned above. A further advantage can be the re-use of the sheet pile walls, if they are recovered after use in temporary applications.

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