

15 years of experience with geotextile encased granular columns as foundation system

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ABSTRACT

The Geotextile Encased Column (GEC) foundation system for earthwork structures built on soils of low bearing capacity was launched onto geotechnical engineering some 15 years ago and is now considered state-of-the-art in Germany. The GEC system provides a geotechnical foundation solution for weak and very weak soils where more traditional ground improvement techniques are unlikely to be viable. This paper provides a system description, the required design procedure and details of ongoing long-term monitoring. Information is also included on the continuous improvements which have been made to the GEC system in response to the technical and financial requirements of large civil engineering projects as well as current potential and research directions and the current regulations and guidelines governing use of the system in Germany. In the future, GECs are likely to be used world-wide for water and land engineering projects in very soft soils.

1. INTRODUCTION

Beginning in 1994, the German contractor Möbius, with the assistance of Huesker Synthetic and Kempfert & Partners, developed a system for the foundation of embankments in soft and very soft soil areas. The general idea was to create an alternative to conventional piles or columns of any kind, and at the same time allow the possibility of constructing compacted gravel (and in reality, sand) columns in very soft soils (Figure 1), which previously would have had insufficient lateral support. Compacted gravel column techniques are usually limited to soft soils with undrained cohesion (undrained, unconsolidated shear strength) $s_u \geq 15 \text{ kN/m}^2$. The problem was solved by confining the compacted sand or gravel column in a high-modulus geosynthetic encasement (Huesker's Ringtrac® GEC). The general idea of Geosynthetic Encased Columns (GEC) is shown in Figure 2. Development of the technology, design procedures [1] and appropriate geosynthetics went hand-in-hand throughout the 1990's. The first projects started successfully in Germany around 1995. Since the inception of GEC's, more than 30 successful projects have been completed in countries including Germany, Sweden, Holland, Poland and Brazil. The GEC system is now accepted as a proven foundation solution and is now included within German design recommendations [2].



Figure 1: Installation of GEC from pontoons in extremely soft mud

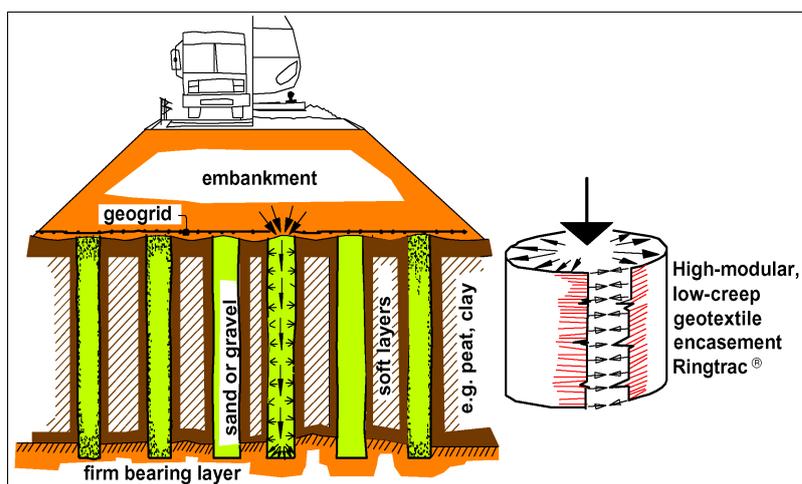


Figure 2: General idea of embankment on soft soil set on Geosynthetic Encased Columns (GEC)

2. GEC - SYSTEM DESCRIPTION

By the GEC-columns the main part of the load from the embankment will be transferred directly through the soft soil down to a firm stratum. Embankments on concrete, steel, and wooden piles are nearly settlement-free. The compression stiffness of the piles is so high, that practically no settlement occurs at the level of pile tops or caps. High strength horizontal geosynthetic reinforcement is typically installed above the piles to bridge over the soft soil between piles and equalize the embankment's deformations.

The vertical compressive behavior of the GECs is less rigid. The compacted vertical sand or gravel column starts to settle under load mainly due to radial outward deformation. The geosynthetic encasement, and to some extent the surrounding soft soil, provides a confining radial inward resistance acting similar to the confining ring in an oedometer, but being more extensible. The mobilization of ring-forces requires some radial extension of the encasement (usually in the range of 1 to 4 % strain in the ring direction) leading to some radial "spreading" deformation in the sand (gravel) columns and resulting consequently in vertical settlement of their top.

The GEC system therefore cannot be completely settlement-free. Fortunately, most of the settlement occurs during the construction stage and is compensated by some increase of embankment height. Finally, ensured by the strength and stiffness of sand or gravel, confining ring-force in the encasement and soft soil radial counter-pressure, a state of equilibrium is reached.

The specific characteristics of the GEC system are:

1. The primary function of the high-modular high-strength geotextile encasement is the radial confining reinforcement of the bearing (sand or gravel) column.
2. The secondary functions of the encasement are separation, filtration and drainage.
3. The system is not completely settlement-free.
4. The GEC is typically an end-bearing element transferring the loads to a firm underlying stratum.
5. The GECs are water-permeable; they practically do not influence the flow of groundwater streams, which has potential ecological advantages.
6. The GECs may also perform as high-capacity vertical drains.
7. The geotextile encasement is a key bearing / reinforcing element, capable of meeting high quality engineered design standards and specifications.
8. It is strongly recommended to install horizontal geosynthetic reinforcement on top of the GECs (at the base of the embankment). The horizontal reinforcement is used for the global stability, for transferring spreading forces or to facilitate load transfer into the columns.

The GEC foundation system was specially developed for earthwork structures built on weak and very weak subsoil. It comprises uniformly arranged columns, filled with non-cohesive material and enclosed in a geosynthetic sleeve, which transmit the structural loads to the bearing stratum (Figure 2).

The overall loads and stress concentrations above the column heads induce outwardly directed radial horizontal stresses in the columns. The particularity of the GEC system is that these stresses are counteracted not only by the inwardly acting pressure of the soft soil, but also – most importantly – by the radial resistance of the geotextile casing of high tensile stiffness (low radial extension).

The substantial circumferential tensile forces generated in the casing provide radial support to the columns and ultimately safeguard the equilibrium of the system, thereby allowing its use even in very soft

soils (and strictly speaking even in air with zero lateral soil support, Figure 3). The arrangement of geotextile-encased columns produces a ductile bearing system that is immune to buckling under the incident column loads. The use of GEC considerably reduces both absolute and differential settlement, while enhancing structural stability both during construction and after completion.



Figure 3: Demonstration of the confining capability of high strength geotextile encasement for GEC “in air”

As the columns also act as filtration-stable (thanks to the sleeve) mega-drains, they speed up the settlement and consolidation process. Later settlement, e.g. caused by traffic loads, is low and can, if necessary, be largely offset by means of temporary cover fill/surcharge. The GEC are arranged in a regular column grid. Based on the unit cell concept (Figure 4), a single column in a virtual infinite column grid can be considered. The influence area A_E of a single column A_C in triangular grid is a hexagonal element, which can be transformed into a circular element with an equivalent diameter D_E (“single cell design concept”).

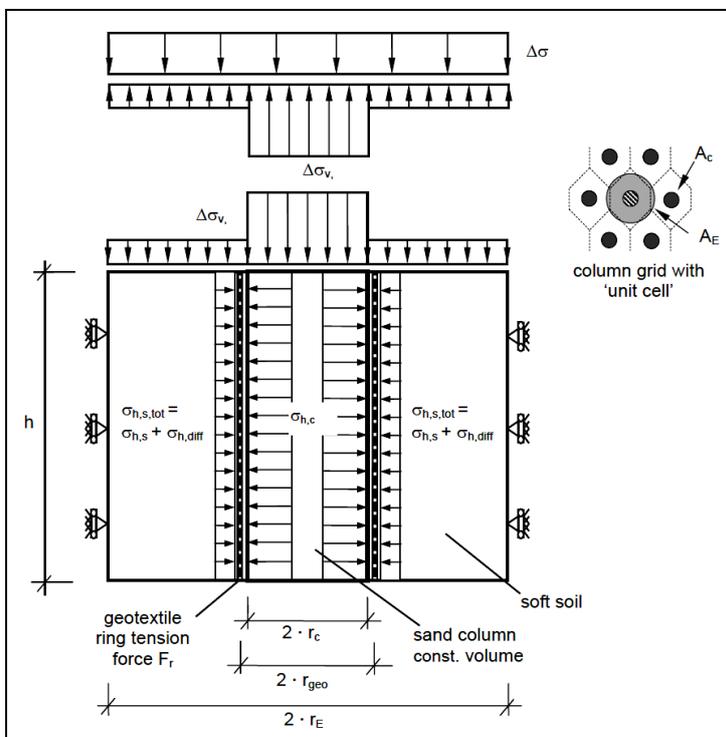


Figure 4: Geosynthetic Encased Column load-bearing system and “single cell” analysis model

Generally the German State-of-the-Art design procedure regarding the vertical and radial GEC-behaviour in the “single cell” is based on a second order theory, say deformations and strains are taken into account

while analysing the systems equilibrium. It reflects the real behaviour of the system including the stress-strain interaction of column fill, surrounding soft soil and the geotextile encasement. Consequently, the results of the procedure described shortly below include not only e.g. the required radial “ring” strength and (important) tensile stiffness of the encasement, but also e.g. the settlement of the top of the columns which controls finally the settlement of the embankment on top of them.

3. GEC: ANALYSIS AND DESIGN

The analysis and design of an embankment GEC foundation consist generally of two steps: First, what is sometimes called “vertical” design, concentrates on the vertical bearing and deformation behavior of the system neglecting overall stability etc. issues.

Second, the global stability (and sometimes the load transfer to the GECs) has to be guaranteed by means of appropriate horizontal geosynthetic reinforcement on top of the columns.

Analysis and design of a GEC foundation is undertaken either using an analytical method [1], [2], [3] or by numerical methods [1]. However, the most commonly adopted method is the analytical method, which is herein described in greater detail and included in the newly published German design guidance [2].

3.1. Column design

The procedure includes a confining force in the ring direction of the encasement based not only on tensile force at failure (“strength”) but on the complete stress-strain behavior of the geosynthetic. This behavior is defined by the tensile stiffness modulus in “ring” direction J , kN/m. Consequently, it is possible to calculate from the ring strain the radial widening of the GEC and the resulting vertical settlement on top of the GEC that will be equal to the average settlement of the embankment.

The bearing elements (GECs) are significantly stiffer than the surrounding soil and therefore attract a higher load concentration from the overlying embankment. Conversely, the pressure acting on the adjacent soil is lowered resulting in an overall reduction of the total settlements.

Generally, an analytical, axial symmetric model [1], [2], [3] is used for calculating and designing a geotextile encased column foundation (Figures 2 & 4) from the point of view of vertical bearing capacity and settlements. The model was developed on the basis of the conventional calculation models used for granular columns [4], [5] and updated to include the effect of the geotextile casing. There is an additional horizontal stress in the column $\Delta\sigma_{h,c}$ due to the additional vertical stress $\Delta\sigma_{v,c}$ over the column head. In view of the equilibrium between the additional surface loading $\Delta\sigma$ and the corresponding vertical stresses on the column $\Delta\sigma_{v,c}$ and the soft soil $\Delta\sigma_{v,s}$, it can be stated:

$$\Delta\sigma \cdot A_E = \Delta\sigma_{v,c} \cdot A_c + \Delta\sigma_{v,s} \cdot (A_E - A_c) \quad (1)$$

The vertical stresses due to the loading and the different soil weights produce horizontal stresses, where $\sigma_{h,c}$ and $\sigma_{h,s}$ are the surcharge stresses in the column and in the soft stratum:

$$\sigma_{h,c} = \Delta\sigma_{v,c} \cdot K_{a,c} + \sigma_{v,0,c} \cdot K_{a,c} \quad (2)$$

$$\sigma_{h,s} = \Delta\sigma_{v,s} \cdot K_{0,s} + \sigma_{v,0,s} \cdot K_{0,s}^* \quad (3)$$

(Note: $K_{0,s}^*$ replaced with $K_{0,s}$ if using the excavation method of installation rather than the displacement method, see Chapter 5)

The geotextile casing (installation radius r_{geo}) has a linear elastic behaviour (tensile stiffness J), whereby the ring tensile force F_R can be transformed into a horizontal stress $\sigma_{h,geo}$, which is assigned to the Ringtrac® geotextile:

$$F_R = J \cdot \Delta r_{geo} / r_{geo} \quad \text{and} \quad \sigma_{h,geo} = F_R / r_{geo} \quad (4)$$

By the use of the separate horizontal stresses, a differential horizontal stress can be defined, which represents the partial mobilisation of the passive earth pressure in the surrounding soft soil:

$$\sigma_{h,diff} = \sigma_{h,c} - (\sigma_{h,s} + \sigma_{h,geo}) \quad (5)$$

The stress difference results in an expansion of the column. The horizontal deformation Δr_s and the settlement of the soft soil s_s are calculated according to *Ghionna & Jamiolkowski* [4]. Assuming equal settlements of column s_c and soft soil s_s , the following calculation equation can be derived (oedometric modulus $E_{S,B}$, poisson ratio ν_B):

$$\Delta r_c = \frac{\Delta \sigma_{h,diff}}{E^*} \cdot \left(\frac{1}{a_E} - 1 \right) \cdot r_c \quad (6)$$

$$s_s = \left(\frac{\Delta \sigma_{v,s}}{E_{oed,s}} - 2 \cdot \frac{1}{E^*} \cdot \frac{\nu_s}{1-\nu_s} \cdot \Delta \sigma_{h,diff} \right) \cdot h \quad (7)$$

with:

$$E^* = \left(\frac{1}{1-\nu_s} + \frac{1}{1+\nu_s} \cdot \frac{1}{a_E} \right) \cdot \frac{(1+\nu_s) \cdot (1-2\nu_s)}{(1-\nu_s)} \cdot E_{oed,s}$$

and

$$a_E = A_c/A_E \quad (8)$$

The relationship between the settlement of the column s_c and the radial deformation at the column edge Δr_c for a constant volume of column material as a function of the original/installed radius r_0 or the original/installed height h_0 is:

$$s_c = \left(1 - \frac{r_0^2}{(r_0 + \Delta r_c)^2} \right) \cdot h_0 \quad (9)$$

A comparability of the horizontal deformations must be given,

$$\Delta r_c = \Delta r_{geo} + (r_{geo} - r_c) \quad (10)$$

There are equal settlements between the column and the soft soil:

$$s_c = s_s \quad (11)$$

At last the following calculation equation can be derived:

$$\left\{ \frac{\Delta \sigma_{v,s}}{E_{oed,s}} - \frac{2}{E^*} \cdot \frac{\nu_s}{1-\nu_s} \left[K_{a,c} \cdot \left(\frac{1}{a_E} \cdot \Delta \sigma_0 - \frac{1-a_E}{a_E} \cdot \Delta \sigma_{v,s} + \sigma_{v,0,c} \right) - K_{0,s} \cdot \Delta \sigma_{v,s} - K_{0,s} \cdot \sigma_{v,0,s} + \frac{(r_{geo} - r_c) \cdot J}{r_{geo}^2} - \frac{\Delta r_c \cdot J}{r_{geo}^2} \right] \right\} \cdot h = \left[1 - \frac{r_c^2}{(r_c + \Delta r_c)^2} \right] \cdot h \quad (12)$$

$$\text{and } \Delta r_c = \frac{K_{a,c} \cdot \left(\frac{1}{a_E} \cdot \Delta \sigma_0 - \frac{1-a_E}{a_E} \cdot \Delta \sigma_{v,s} + \sigma_{v,0,c} \right) - K_{0,s} \cdot \Delta \sigma_{v,s} - K_{0,s} \cdot \sigma_{v,0,s} + \frac{(r_{geo} - r_c) \cdot J}{r_{geo}^2}}{\frac{E^*}{(1/a_E - 1) \cdot r_c} + \frac{J}{r_{geo}^2}} \quad (13)$$

By adopting this deformation, the only unknown variable is $\Delta \sigma_{v,s}$. The equation can be solved iteratively by estimating this variable (although use of suitable software is recommended due to the potentially time consuming process of undertaking this by hand). More details are shown in Raithel [1] and also in Raithel & Kempfert [3]. It is important to note that the stress-strain behavior of the encasement is the key element for the performance of the system. Note also that the tensile stiffness modulus J is a time dependent parameter due to the creep strain of the encasement. Also from this point of view (say deformation long-term control) low-creep encasements have to be preferred.

3.2. Horizontal reinforcement design

The horizontal reinforcement (Figures 2 & 6) is used to ensure global stability, to taking over spreading forces as well as to facilitate if necessary (see below) load transfer into the columns and to equalize settlements.

Load transfer into the GEC is achieved primarily by the formation of stress arches in the embankment over them. Some additional support may be necessary similar to the situation with reinforced embankments on rigid piles (“membrane” or “bridging” function of the horizontal reinforcement). Generally, designing the horizontal reinforcement layers above the column heads for membrane forces can be dispensed with. However, the application of horizontal reinforcement for “membrane” bridging action is dependent upon the stiffness ratio between the column (stiffness $k_{s,T}$) and the soft soil (stiffness k_s) [2], see herein Table 1 corresponding to Table 10.2 in [2].

Table 1: Requirement for designing horizontal reinforcement for membrane forces as a function of stiffness ratios

Zone	Stiffness ratio	Design of horizontal geosynthetic reinforcement
I	$k_{s,T}/k_s \leq 50$	Design unnecessary
II	$50 < k_{s,T}/k_s \leq 75$	Design recommended
III	$k_{s,T}/k_s > 75$	Design necessary

For Zone 1 the horizontal reinforcement is installed as a structural element to satisfy global stability and/or to transfer spreading forces. For Zone 2, although significant changes in load behavior or larger settlements are not anticipated, in certain cases it may be necessary to design the reinforcement to act as a load transfer “membrane” component. For Zone 3, where the stiffness ratios are higher, the effectiveness of the foundation system is no longer guaranteed without designing the horizontal reinforcement for membrane forces. A minimum reinforcement is required using design resistance R_{Bd} no matter which zone is relevant. If it is necessary to design the horizontal reinforcement for membrane forces, then the appropriate methodology should be adopted [2].

For the GEC-System the second main function of horizontal reinforcement (to ensure global stability and to take over spreading forces) controls its design. Common geotechnical design procedures (as Bishop or Janbu) can be used modified by the presence of the horizontal reinforcement and additionally by the higher “mixed” strength of soft subsoil due the GECs [2].

The final result of the design of GEC-Foundation is a flexible, ductile, to a significant extent self-regulating and thus robust system, what can be in many cases a key advantage. Self-regulating load bearing behavior means that if the columns yield, the load is redistributed to the soft stratum, thereby increasing the ground resistance supporting the columns, which in turn leads to load redistribution back into the columns.

4. DESIGN POSSIBILITIES TO INFLUENCE THE SYSTEMS BEHAVIOR

Following are several options to control settlement and the vertical bearing capacity of the system:

1. Increase the percentage of column area to the total area (usually 10% to 20%) by increasing the diameter of GEC (usually 0.6 to 0.8 m) and/or decreasing their spacing (usually 1.5 to 2.5 m).
2. Use a better quality fill for the columns (e.g. gravel instead of sand).
3. Increase the tensile stiffness and strength of the ring direction of the geosynthetic encasement thus reducing settlement and increasing single column bearing capacity. The higher the tensile stiffness, the less the radial strain and consequently the compressibility of the column; this results in less settlement.

Additional information on the influence especially of the ring tensile stiffness and area ratio can be found e.g. in [6, 7]. Usually the increase of the ring tensile stiffness is the most flexible and powerful tool to reducing settlement and increasing bearing capacity.

And last but not least: the encasement has to be seamless - this results in significantly higher guaranteed strength and in a homogeneous stress-strain behavior in the most important bearing ring direction (Figure 5).

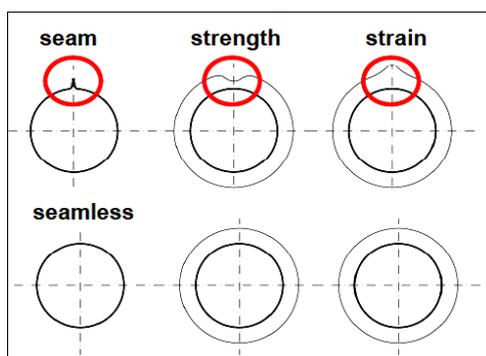


Figure 5: Difference between seamed and seamless encasements in terms of stress-strain behaviour



Figure 6: Example of horizontal geosynthetic reinforcement on top of already covered GECs for heavy loaded sensitive runways (left) and under a land reclamation embankment (GECs still visible) (right)

5. INSTALLATION METHODS

Two different options are generally available with regards to the GEC construction technology. The first option is the displacement method (Figure 7) where a closed-tip steel pipe is driven down into the soft soil followed by the insertion of the circular weave geotextile (Figure 8) and sand or gravel backfill. The tip opens, the pipe is pulled upwards under optimized vibration designed to compact the column. The displacement method is commonly used for extremely soft soils (e.g. $s_u < 5 \text{ kN/m}^2$) and/or where vibrations are not important.

The second construction option is the replacement method (Figure 9) with excavation of the soft soil inside the pipe. This method uses an open pipe where special tools remove the soil during or after driving the pipe down into the ground. The rest of the operation is identical to the displacement method. The excavation method is likely to be preferred with soils with high penetration resistance or when vibration effects on nearby buildings and road installations have to be minimised.

The advantage of the displacement method compared to the excavation method is based on the faster and more economical column installation and the effects of pre-stressing the soft soil. Furthermore it is not necessary to excavate and dispose soil. The excess pore water pressure, the vibrations and deformations have to be considered.

There are two options available when selecting the diameter of the circular weave geotextile (Ringtrac®). In the first option the diameter of the circular geotextile is slightly larger than the diameter of the steel pipe, thus allowing for a better mobilization of soft soil radial counter-pressure after extracting the pipe. The disadvantage is a larger column settlement based on the larger radial deformation due to an “unfolding” phase prior to mobilization of the geotextiles tensile modulus. In the second option, the diameter of the geotextile and the pipe are the same. This provides for a quick strain–tensile ring force mobilization, which results in less soft soil mobilization and higher ring-tensile forces, but in reduced settlement. The equal diameter option is preferred at present.

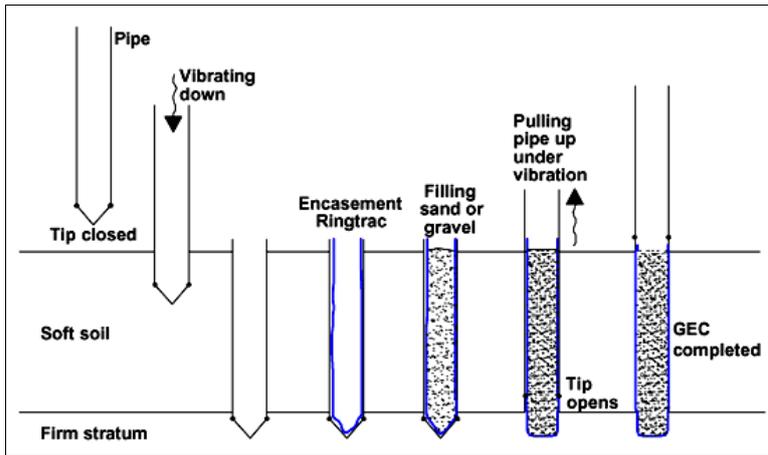


Figure 7: Displacement method of construction



Figure 8: Installation of geotextile encasement (displacement method)

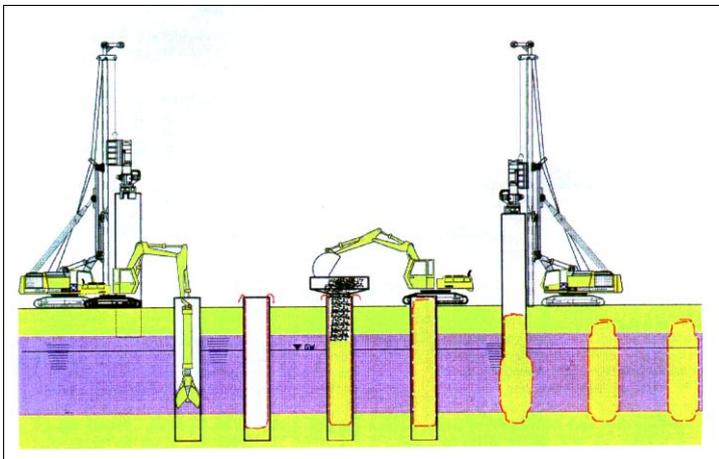


Figure 9: Replacement method of construction



Figure 10 : Completed columns

6. GEOTEXTILE ENCASUREMENT SELECTION

As previously explained the ring tensile stiffness and strength can influence the behaviour of the system significantly. The geotextile is required to support the horizontal radial stress variance for the design life of the structure.

In order to maintain the equilibrium state, designers need to have confidence in the long-term behaviour of the geotextile which provides radial support to the columns over their service life. In this regard, not only is the design strength of the encasing geosynthetic important, but so is the short- and long-term stress/strain behaviour. Insufficient radial support due to low ring-tensile modulus (in the short- or long-term) would result in bulging of the columns and redistribution of the horizontal and vertical stresses, resulting in potential large settlement of top of the GEC (i.e. and the embankment), and in a proportional increase in the vertical stresses acting on the adjacent soft soil thereby leading to further settlement. Partial or total loss of radial support would exacerbate this settlement, which could lead to settlements exceeding serviceability limits or even result in ultimate limit state conditions for the system.

The long-term behavior of geotextiles has long been an issue with designers, however extensive research on their durability and long-term behavior, including creep, mechanical damage and environmental degradation, have helped to allay most of these concerns. The polymer employed largely determines the properties of the encasement. The design engineer's ideal geosynthetic reinforcement would possess the following characteristics [8]:

- high tensile modulus (low strain values compatible to the common strains in soils, rapid mobilisation of tensile force)
- low propensity for creep (high long-term tensile strength and tensile modulus, minimum creep extension, lasting guarantee of tensile force)
- high permeability (lowest possible hydraulic resistance and as a result, no increasing pressure problems)
- little damage during installation and compaction of contacting fills
- high chemical and biological resistance

In the specific case of GEC the geotextile reinforcing encasement may not include joints or seams. This guarantees no weak zones without any reduction factors for joints and a constant tensile stiffness around the entire bearing ring direction. Up until now, the project designs required short- and long-term tensile stiffness from $J = 1.500$ to 6.000 kN/m and ultimate tensile ring strengths from 100 to 400 kN/m. Higher moduli and/or strengths have been also used for particular projects.

7. LONG TERM MEASUREMENTS OF THE GEC SYSTEM

7.1. General

The determination of residual settlement requires consideration of both primary settlement and secondary or creep settlement. The latter invariably determines the settlement behaviour of GEC foundations in service, given that primary settlement is accelerated through the action of the encased columns as large vertical drains and has usually abated by the end of the construction period.

The background literature [9], [10], describes how creep settlement is proportional to those changes in load that bring about deformation. As the stress concentration over the column heads entails a reduction

in the loads acting on the soft stratum, creep settlement is likely to be lower where encased columns are used than in unimproved subsoils. Moreover, where creep settlement is allowed for, the soft stratum undergoes a greater degree of settlement than the column.

Consequently, the interactive bearing system will normally bring about a redistribution of loads, with a higher proportion borne by the encased columns, and ultimately a new equilibrium state with even lower levels of stress in the soft soil. This, in turn, will further lower the degree of creep settlement in comparison to the unimproved scenario.

The achievement of reductions in creep settlement has been confirmed by long-term measurements.

7.2. Extension of AIRBUS Hamburg-Finkenwerder site at "Mühlenberger Loch"

This project, which was presented among others at the Austrian Geotechnical Conference in 2001, was successfully implemented between 2001 and 2004. Completed in September 2002, the 2,500 m long dike enclosing the extension area was founded on a total of approximately 60,000 GECs. As part of the structural checks on the ground engineering concept, the stability and deformation predictions were verified by on-site measurements during construction. The comprehensive measurement instrumentation included horizontal and vertical inclinometers, settlement indicators and measurement marks, as well as water pressure and pore-water pressure transducers. Most of the measurement instrumentation was designed for continued monitoring after completion of the dike. Typical results are shown in Figures 11 & 12.

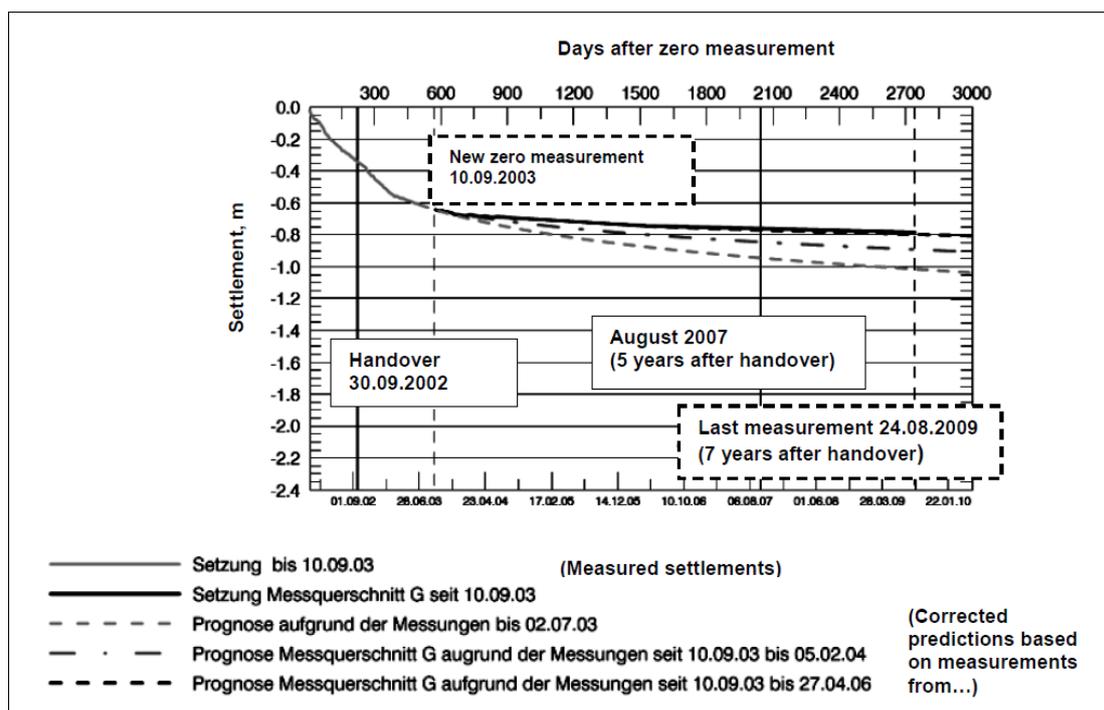


Figure 11: Results of long-term measurements and comparison with creep settlement predictions for foundation to dike enclosing extension to aircraft production site at Hamburg-Finkenwerder

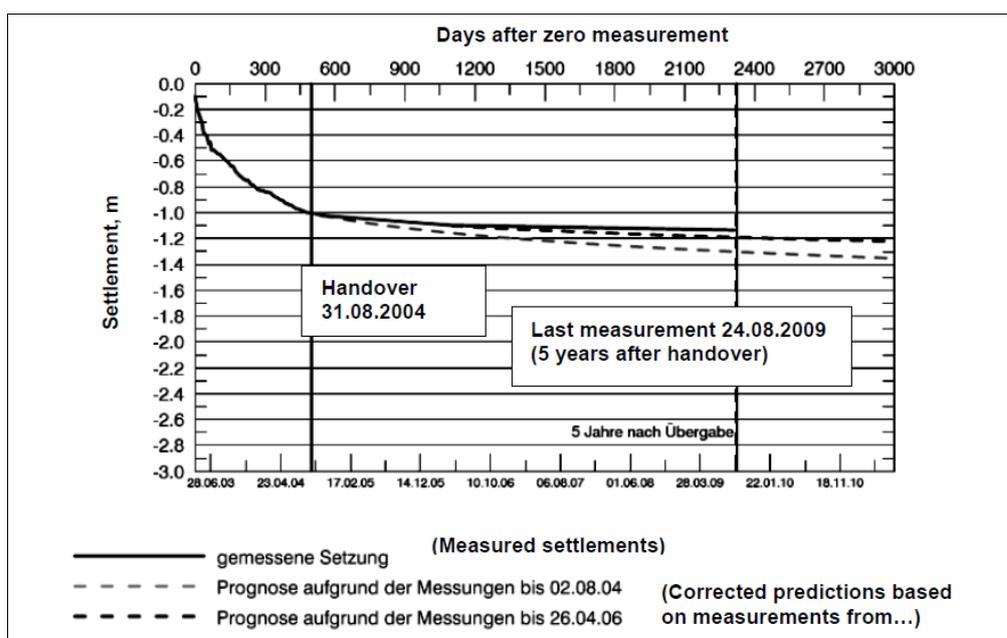


Figure 12: Results of long-term measurements and comparison with creep settlement predictions for GEC foundation to front Finkenwerder dike

The dike camber provided to offset long-term settlement was first checked when primary settlement was practically complete after roughly one year. A computational prediction was then made of further creep settlement. A further check in 2004 already revealed significantly lower creep settlement than initially forecast. A new prediction was then made using creep factors derived from the measurements by means of logarithmic regression functions. The predictions were revised again in 2006 on the basis of further settlement measurements and these have since proved to reliably model the pattern of creep settlement measured over the last eight years or so. The GEC foundation of the front Finkenwerder dike, which is a continuation of the dike enclosing the AIRBUS site extension, has exhibited similar behaviour. As Figures 11 and 12 indicate, a significant downward adjustment of creep settlement predictions proved necessary for both dike structures.

7.3. Widening of A115 motorway embankment near Saarmund, Germany

A project to widen the A115 motorway south of Potsdam to six lanes started in the summer of 1998. At one point, the motorway embankment crosses an approx. 300 m wide strip of low-lying land comprising organic soils. The existing embankment was built using the bog blasting method. To widen the embankment in the low-lying area, 80 cm diameter GEC were installed on a 10% grid.

Horizontal and vertical inclinometers were incorporated during construction to monitor the deformation behaviour of the embankment. Readings from two of the horizontal inclinometers have been taken up to the present. Figure 13 shows a typical time-settlement curve. Creep settlement in the order of max. 1-2 cm has been measured over the past seven years.

7.4. Creep settlement for GEC foundations

The above and other settlement measurements suggest that the application to GEC foundations of creep factors specified for or derived from unimproved subsoils (i.e. without column foundations) leads to a significant overestimation of creep settlement compared to actual effective behaviour. Suitable laboratory tests (creep tests) would appear to be a prerequisite for the accurate prediction of long-term deformation and creep settlement. These would allow derivation of the creep behaviour of soft strata under various loading conditions and levels, and thereby permit quantification of the creep-settlement-reducing impact of GEC foundations.

Given the lack of suitable test results, however, a reduction factor derived from measurement results is frequently applied, by way of approximation, to the creep settlement determined for the unimproved subsoil.

On the basis of comparisons between computational predictions and measurements, the reduction factor to be applied to the creep settlement for the unimproved subsoil is estimated at between 0.25 and 0.50, depending on the project parameters. In other words, GEC foundations achieve an approx. 50-75% reduction in creep settlement.

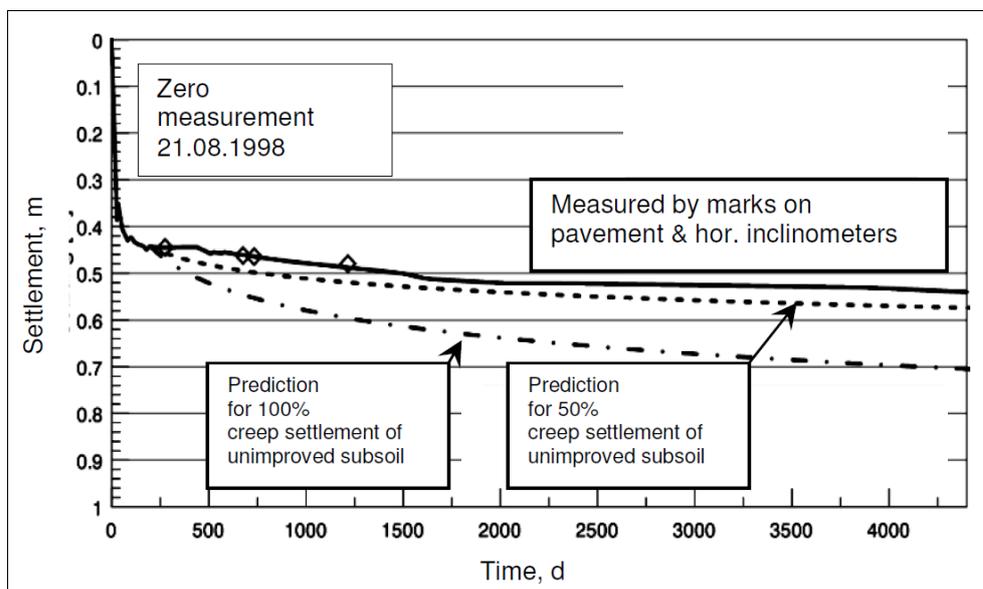


Figure 13: Time-settlement curves of representative cross-section of A115 motorway near Saarmund

8. FURTHER SYSTEM REFINEMENTS

8.1. Waterproofing against rising groundwater

Where the GEC foundation is sunk into a water-bearing sand/gravel horizon, the columns create a hydraulic connection between the ground surface and the aquifer. Apart from the risk of groundwater-polluting substances infiltrating into the subsoil, any existing artesian pressure may result in a constant upward flow of groundwater and a discharge at ground level that limits the water pressure in the column. The water permeability of the GEC can be minimized by installing a sand/bentonite mix in the body of the column. Here, the stiff geotextile sleeve plays an important, if not decisive, role. This solution has undergone a series of comprehensive in-situ tests by J. Möbius Bau GmbH and has already been successfully deployed in several road construction projects in Northern Germany.

Figure 14 shows part of a production drawing for a GEC foundation for a road embankment. In this case, the 1 m high waterproof barrier is located at the foot of the columns. The level of the barrier can, however, be adapted to the particular subsoil stratification (e.g. location at column head in case of intermediate sand aquifers).

8.2. Geotextile casing

The process of refining and optimizing the GEC system has also resulted in developments to the Ringtrac[®] geotextile casing. As a key reinforcing structural element, the casing significantly influences the load bearing and deformation behaviour of the column and overall system. The requirements placed on integrity, durability, robustness, mechanical behaviour etc. are accordingly high. Of particular importance is the decisive role by the circumferential stiffness (tensile modulus) in addition to the tensile strength [9]. To create ample scope for system optimization, the provision of a wide range of Ringtrac[®] diameters, tensile strengths and circumferential tensile moduli is essential, though time (permanent loading, creep, creep strain) is also a significant factor. To meet these demands, three seamless Ringtrac[®] lines made from different polymers are now available with diameters between 50 cm and 100 cm, short-term circumferential strengths of 400 kN/m or more, and circumferential stiffnesses (circumferential tensile moduli) ranging from 1000 kN/m to 8000 kN/m. The choice of polymers also guarantees high resistance, e.g. in alkaline environments. The wide variety of casing products thus offers considerable potential for system optimization.

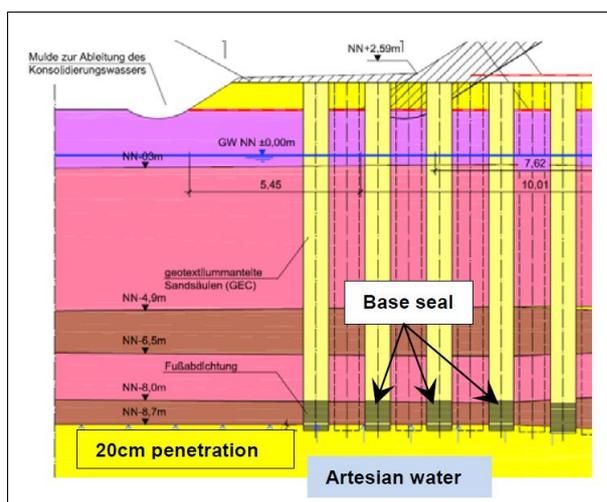


Figure 14: GEC with base seal – excerpt from highway production drawing

8.3. Column length

A construction project in Poland necessitated the installation of GEC with a maximum length of nearly 30 m. Refinements to the driving equipment allowed the installation of columns to a depth never previously achieved. The A2 motorway, handed over to traffic in December 2011 and linking the city of Poznań with the German-Polish border, crosses an approx. 300 m long channel with organic sediment. Ground conditions comprise peat and gyttja mud, with undrained shear strengths well below 10 kPa in some cases, are present in thicknesses up to 28 m below ground level. Installation of the longest columns – 800 mm in diameter, with an open pipe and lost base plate – using the displacement method was achieved with the help of a high-performance belt vibrator (Figure 15). For the longest columns, the inner surface of the displacement pipe was lubricated by means of an extra-lean bentonite suspension as a means of reducing the friction forces between pipe and column.



Figure 15: LRB 255 rig with 30 m long displacement pipe on construction site in Poland

8.4. Trial loading of a column group

A trial loading of a group of GEC, which will provide a better understanding of system behaviour, was carried out in February and March 2011. The loads applied to the 10-column group were gradually stepped up until one of the limit states was reached. Standard computational methods have been used to calculate the magnitudes of the action needed to achieve the "base failure" and "geotextile casing failure" limit states. The tests were adopted the same parameters as the calculations. The system behaviour was

closely monitored during the tests by means of detailed measurements and subsequently compared with the computational results. The aim of this procedure was to identify and quantify the structural reserves offered by the system. First results and analyses were published separately [15].

8.5. Acoustic ground investigation methods

Additional ground investigations are performed at the design stage to determine the required sinking depths for the columns. During installation of the columns, the equipment parameters are used to check for compliance with the specified sinking depth. As a rule, these clearly indicate the point at which adequately strong soil has been reached. In exceptional cases, e.g. with closely graded, loosely packed fine sands, the horizon to which the columns are to be sunk cannot be identified precisely enough. This leads to extended columns and increased effort for structural checks, e.g. due to further ground explorations.

An additional ground investigation method that uses acoustic techniques for the identification of adequately strong subsoils is currently under development by J. Möbius Bau-AG in collaboration with Clausthal University of Technology. This involves the transmission of signals, via a protected cable, from an accelerometer fitted at the tip of the pipe to a receiver at the pipe head, and from there by radio to the operating cabin. Here, a special software application filters the data and provides the operator with a simple visual indication of the soil type in which the pipe tip is currently located (Figure 16). The procedure results in a both safe and economical solution.



Figure 16: Displacement pipe equipped with measurement instrumentation to record acoustic signals

9. NEW POTENTIAL APPLICATIONS

9.1. Incorporation behind quay walls

Harbour construction projects frequently involve the placing of backfill behind newly built walls. Here, the fill is often placed on top of highly compressible soft strata with low shear resistance. The high earth and pore water pressures typically encountered in such cases necessitate an extremely compact wall construction.

In the initial state, i.e. prior to the onset of settlement and action of the geotextile casing in load transmission, the GEC already serve as a simple ground improvement measure due to the sand component incorporated in the soft stratum. The resulting increase in shear resistance is factored into the structural calculations for the subsequent states. In addition to this, some of the backfill loads are transmitted to the bearing subsoil via the GEC without imposing any horizontal earth pressure on the wall. Close control of the backfilling process is, however, necessary to exploit this effect. The backfill has to be placed in layers, with adequate time allowed for consolidation. The reduced earth pressure thus achieved automatically paves the way for an optimized and economical quay wall solution. Figure 17 shows a production drawing (cross-section) for a new quay wall at the Europakai docks in Hamburg.

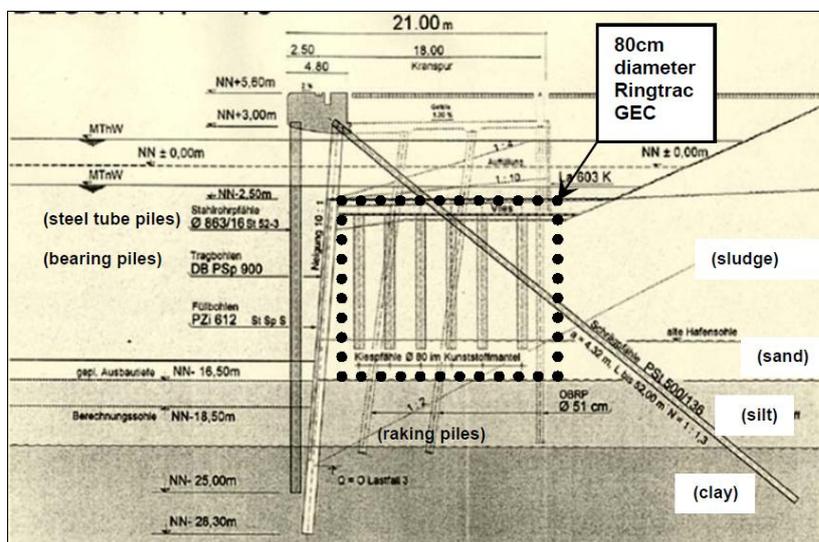


Figure 17: GEC behind new quay wall at Hamburg docks

9.2. Earthquake regions

In examining the action of GEC in earthquake regions, a distinction must be drawn between the applications and mechanisms relevant to different subsoil conditions.

In the case of primarily coarse granular soils, such as silty or poorly graded sands, that are prone to liquefaction under earthquake loads on account of their grading and low packing density, the use of ground improvement measures such as vibrated stone columns (to improve strength and density) is now state of the art.

The mechanisms that operate with GEC are essentially the same as those for stone columns, albeit with the added bonus of the reinforcement provided by the casing:

- a) Increased resistance to slope or soil shear failure in the event of an earthquake
- b) Ultimate confinement and strengthening of the non-cohesive columns
- b) Reduction of pore water overpressures through subsoil drainage accompanied by the additional separating and filtering functions of the geotextile encasement, thereby preventing liquefaction effects where liquefaction-prone soils (e.g. loosely packed fine sands) are present, as well as
- c) Reduction of seismic shear stresses in subsoil through columns and improvement of damping properties of subsoil

Irrespective of these mechanisms, it should be remembered that greater quake intensity, a longer quake duration, a higher water table and a lower packing density all serve to increase the liquefaction risks. Hence, an improvement already results from compaction of the surrounding soils achieved by sinking the pipe. The displacement method is, of course, more effective than the excavation method in this regard. The more compact soil conditions resulting from the column installation process are thus one of various factors that combine to enhance earthquake resistance.

A further application in the field of earthquake protection involves the use of GEC in soft, cohesive or organic soils that essentially provide little lateral support to the columns.

In the event of an earthquake, the seismic loads in such soils are likely to bring about widespread and virtually complete structural failure, which, in the absence of an additional foundation system, would inevitably lead to the failure of any existing superstructure. No increase in structural stability can be achieved in such cases through the use of vibrated stone columns or other non-encased systems as these will likewise suffer a more or less complete loss of their bearing capacity in the event of an earthquake, due to the lack of adequate lateral support. Similarly, piles, despite their inherent load bearing strength, would be highly susceptible to buckling.

With GEC, on the other hand, the supporting effect of the casing will ensure adequate short-term bearing capacity, even in the absence of any lateral support to the columns from the surrounding soil during the earthquake. Hence, in addition to their familiar advantages in terms of structural behaviour, GEC foundation systems can also be used to provide enhanced earthquake resistance.

9.3. Increase in dynamic performance of railway lines

The term "dynamic stability" is frequently used in the assessment of earthworks where particular allowance is needed for cyclic and dynamic action from rail traffic. This concept has, however, also been used in relation to the increasing settlement of the track over time that results from the soil behaviour under the dynamic loads imposed by rail traffic - even though this merely constitutes a gradual loss of serviceability, rather than a failure of structural stability.

As practical experience and the relevant literature [11] suggests, soft cohesive soils along with organic and organogenic soils, in particular peat, must be deemed critical in terms of their dynamic stability and performance. Particularly in the frequent case of rail sections that require enhanced maintenance due to their non-standards-compliant substructure or vibration-sensitive subsoils, or due to a planned increase in train speeds or frequency along the relevant rail section, the assessment of the subsoil's dynamic stability generally dictates the choice of rehabilitation method.

The shear strain γ occurring in soils under dynamic action [12] is regarded as the key parameter in the assessment of long-term dynamic stability and dynamic performance. Any such assessment needs to determine whether, under the dynamic action of rail traffic, that volumetric cyclic threshold shear strain $\gamma_{v,U}$ is reached whose exceedance is likely to bring about, within a short period, a level of deformation that could no longer be offset, for example, by packing. The computational model for this situation turns out to be relatively complex due to the interaction between track-dynamic [13] and soil-dynamic FEM computations [14].

The use of GEC in existing soft strata entails a reduction in dynamic action in these vibration-sensitive soils. This, in turn, significantly increases dynamic stability and performance, and allows higher train speeds.

One key advantage of GEC in such applications results from the use of geosynthetic materials and their linear-elastic behaviour. This guarantees the integrity and flexible, self-regulating structural performance of the columns over their entire lifespan.

Due to their greater flexibility and the adaptable reaction of the subsoil to the track superstructure and dynamic loads imposed by rail vehicles, GEC foundations offer distinct advantages over rigid systems such as piles or concrete columns. Moreover, GEC help to minimize problems at the junctions between rehabilitated and non-rehabilitated sections.

It should also be noted that, unlike non-encased granular (e.g. vibrated stone) columns, GEC are protected over their entire lifespan, thanks to the filtration stability of the geotextile casing, from the inward migration of surrounding soil, even under the dynamic loads imposed by rail traffic. The use of GEC thus ensures dynamic stability and performance during the entire lifespan or service life (i.e. 50-100 years) of the structure.

10. SUMMARY

Some 15 years after their market launch, geotextile-encased columns (GEC) have evolved into a sophisticated and absolutely reliable earthwork foundation system, underpinned by both theory and practice. Due to the confining encasement of the columns in the GEC-system it can be applied even in extremely soft soils with e.g. $s_u < 2$ kPa, which is in fact more a suspension than a soil. In particular, the system's long-term behaviour can now be accurately predicted, subject to the usual tolerances applicable to creep settlement calculations for foundations on organic soils.

In Germany, GEC foundation systems are governed by Section 10 of the current edition of the EBGEO (Recommendations for Design and Analysis of Earth Structures using Geosynthetic Reinforcements) issued by the German Geotechnical Society (DGGT). This describes the associated terminology, mechanisms, applications, production methods, design recommendations, materials, computational procedures and test criteria. In Germany, then, GECs have been definitively acknowledged as state-of-the-art technology.

The advantages of the GEC system, particularly for soft strata with extremely low shear resistances, are not only demonstrable by computational methods, but have also been substantiated by measurement results.

Ongoing refinements to the system are based on the standard EBGEO guidelines effective in Germany. Various research and development projects are currently in progress with the aim of improving the reliability of on-site installation and widening the scope of application of the GEC foundation system.

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