

Geotextile Encased Columns (GEC): Load Capacity, Geotextile Selection and Pre-Design Graphs

Dimitar Alexiew¹, Daniel Brokemper² and Steve Lothspeich³

¹Dr.-Ing., Head of Engineering Department, HUESKER Synthetic GmbH, 48712 Gescher, Fabrikstrasse 13-15, Germany, PH +49 (2542) 701290, FAX + 49 (2542) 701493, at@huesker.de

²Dipl.-Ing., Engineering Department, HUESKER Synthetic GmbH, 48712 Gescher, Fabrikstrasse 13-15, Germany, PH +49 (2542) 7801293, FAX + 49 (2542) 701493, brokemper@huesker.de

³P.E., HUESKER inc., P.O.Box 411529, Charlotte NC 28241, USA, PH +1 (800) 9429818, FAX +1(704) 5885988, slothspeich@huesker.com

Abstract

Embankments over soft subsoils supported by piles or stone columns have several advantages over the classical unsupported embankment foundation when compared in terms of bearing capacity, serviceability, and duration of construction. In extremely soft soil conditions, lateral support can be problematic for stone columns. An alternative system, which can both provide the required lateral support and increase bearing capacity, is the “Geosynthetic Encased Columns” (GECs). This system includes a high-modulus, creep resistant geotextile encasement called Ringtrac[®] that confines the compacted sand or gravel column thereby providing constructability and bearing capacity even in extremely soft soil. The following describes the design principles, technologies and procedures developed over the past ten years and the importance of the geotextile encasement’s tensile modulus. Also presented are graphs showing the influence of different factors on settlement. They could be also used in preliminary designs for orientation and proper encasement selection.

1. Introduction

Beginning in 1994, the German contractor Möbius and HUESKER Synthetic developed a system for foundation of embankments in soft soil areas. The general idea was to create an alternative to the conventional piles of any kind and to eliminate at the same time the impossibility of constructing compacted stone columns in very soft soils due to insufficient lateral support. Compacted gravel column techniques are usually limited to soft soils with undrained cohesion (undrained, unconsolidated shear strength) c_u or $s_u \geq 15$ kN/m². The problem was solved by confining the compacted sand or gravel column in a high-modulus geosynthetic encasement. The general idea of Geosynthetic Encased Columns (GEC) is shown in Figure 1. Development of the technology, design procedures and

appropriate geosynthetics went hand in hand throughout the 1990^{ies}. The first projects started successfully in Germany around 1995. In the meantime, the solution with GECs proved to be very efficient for more than 15 projects including the Airbus land reclamation on sludge near the city of Hamburg in 2001-2002. More detailed information about pertinent projects is presented by Kempfert et al (2002), Nods (2002), and Raithel et al (2002).

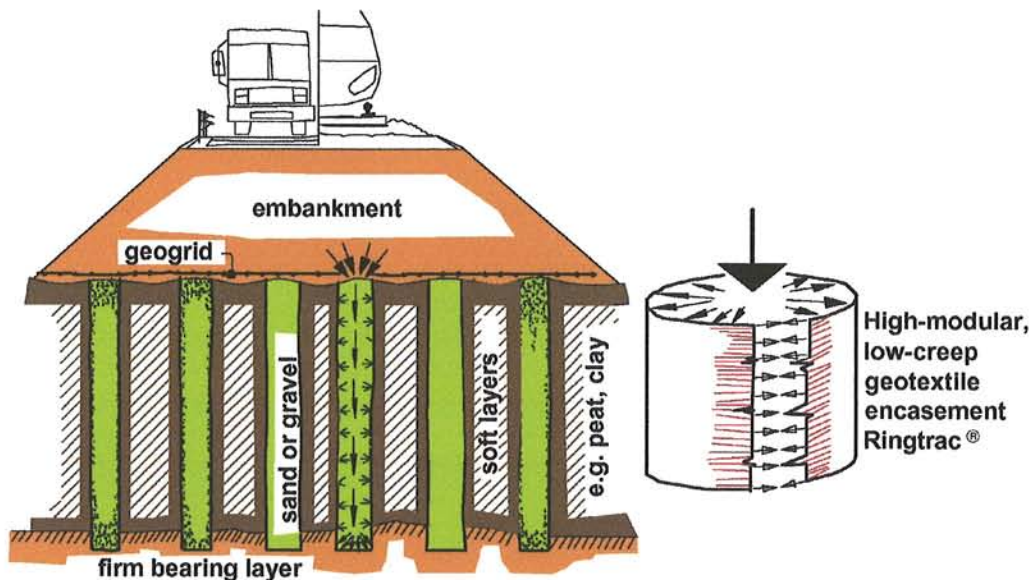


Figure 1. General idea of embankment on soft soil set on Geosynthetic Encased Columns (GECs)

The specific characteristics of the GEC system are:

1. The primary function is the radial confining reinforcement of the bearing column.
2. The secondary functions 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 its ecological advantages.
6. The GECs also may perform as high-capacity vertical drains, although it is not their primary function.
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 GECs (in the base of embankment) in order to equalize settlements, to bridge the soft soil, to increase global stability, and to control spreading forces. The situation is similar to embankments on traditional piles, and is beyond the scope of this paper (see e.g. Alexiew 2002).

2. General concept, mechanisms of functioning and design options

The general concept remains the same as for conventional piled embankments: to “take over” the load from the embankment and to transfer it directly through the soft soil down to a firm stratum. One difference: embankments on concrete, steel, and wooden piles are nearly settlement-free. If the design is appropriate, 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 GEC’s 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.

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

- A. 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).
- B. Use a better quality fill for the columns (e.g. gravel instead of sand).
- C. 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 in the ring direction the lower the radial strain, the lower radial outward deformation of the column fill, and resulting settlement at the top of the column.

The ring tensile stiffness (tensile modulus) and strength can influence the behavior of the system (e. g. the settlements) in a significant way as shown later herein. In Figure 2, the short-term strain vs. tensile ring force of a high modulus GEC fabric is depicted. Note, that for an appropriate design both the short-term and long-term tensile modulus are taken into account. The typical estimation of short- and long-term tensile modulus J , kN/m, of the circular weave geotextile is shown in Figure 3, in which time $t_2 > t_1$. The long-term modulus used in the design is obtained from the product specific isochrones. Low strain creep resistant polymers are

required in the manufacturing of geotextile encased column materials to control post construction strains and settlements.

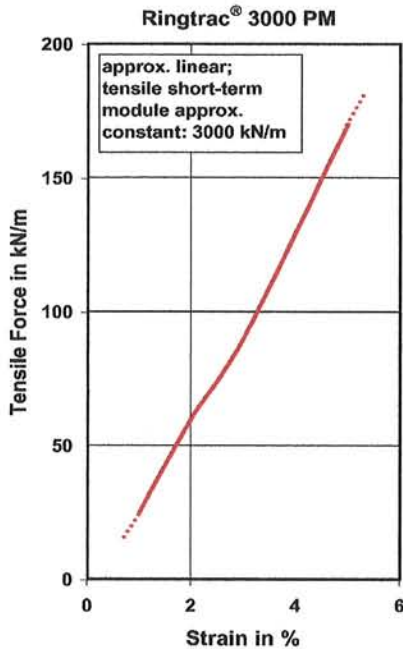


Figure 2. Typical graph of tensile force vs. strain (short-term) for a Ringtrac®

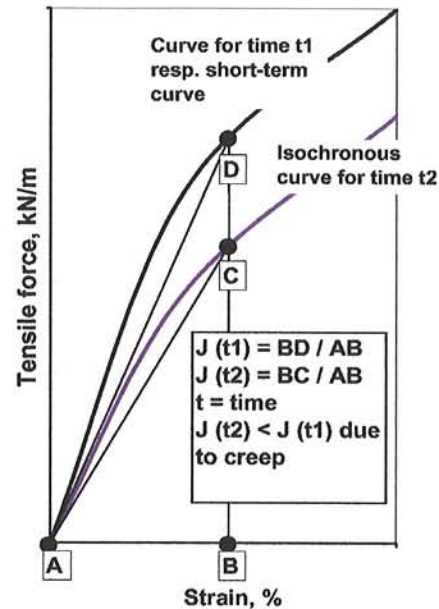


Figure 3. Typical estimation of short- and long-term tensile modulus J , kN/m

3. Construction technologies and options to controlling the systems behavior

Two different options are generally available with regards to the GEC construction technology. The first option is the displacement method where a closed-tip steel pipe is driven down into the soft soil followed by the insertion of the circular weave geotextile and sand or gravel backfill (Fig. 4). 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. $s_u < 15 \text{ kN/m}^2$). The second construction option is the replacement method 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.

There are two options available when selecting the diameter of the circular weave geotextile. In the first option the diameter of the circular geotextile is a bit 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 “unfolding” phase prior to mobilization of the geotextile’s 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. In Figure 5 free-standing GEC after construction “in air” for demonstration purposes are shown.

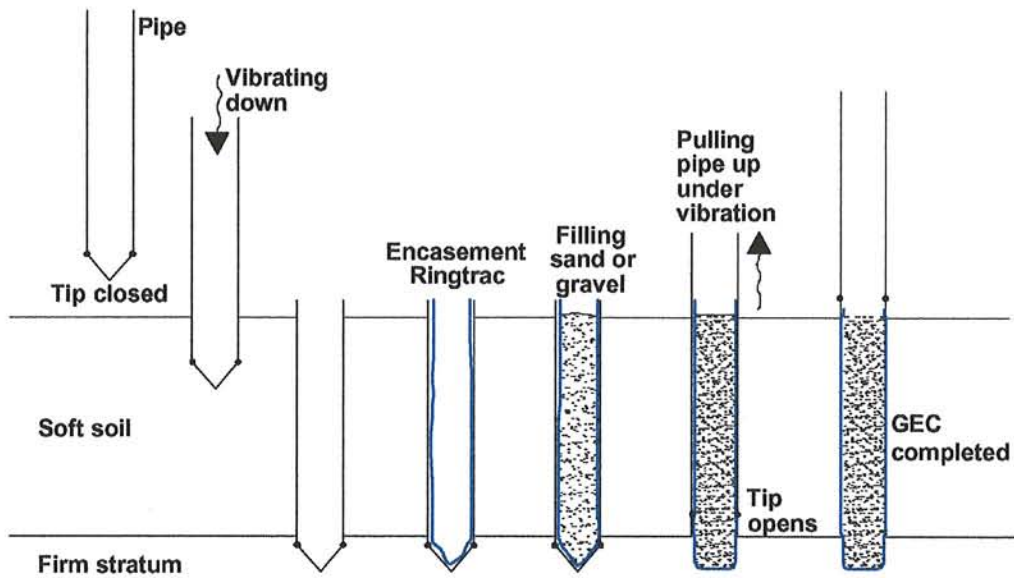


Figure 4. Displacement method of construction



Figure 5. Test Ringtrac®-GEC constructed “in air” for demonstration in different testfields

4. Design and calculation methods

For design and calculation purposes different methods have been developed over the years. At present, both analytical design procedures and numerical solutions are available. Initial steps in the calculation process were first suggested by Van Impe (1989) and numerical as well as more precise analytical models developed by Raithel (1999), and Raithel & Kempfert (2000).

The analytical design procedure by Van Impe (1989) allows an estimation of the required tensile strength of the encasement in the ring direction but does not provide the ability to take strain deformations into consideration nor to calculate the settlement of the embankment. The design method analyzes the problem only from the point of view of tensile strength while ignoring the corresponding ring strain. (Although the latter causes a radial widening of the GEC resulting in vertical settlements).

Raithel (1999) presented two new analytical design procedures on the basis of established design procedures for vibro-displacement compaction by Priebe (1995) and Ghionna & Jamiolkowski (1981). The first one is called "simplified" herein, the second one "precise". Raithel's procedures include 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 J , kN/m (Fig. 3). 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. Further assumptions and details regarding also the differences between the simplified and the more precise design procedure can be found in Raithel (1999). It is important to note that the stress-strain behavior of the encasement is the key element for the performance of the system.

For many projects, in situ measurements have confirmed the correctness and applicability of the more precise procedure mentioned. The largest and most sophisticated project constructed to date was a land reclamation along the Elbe River close to the city of Hamburg for the new Airbus plant. For this project over 60,000 GECs with a total length of the confining reinforcement of more than 700,000 m were installed below the dikes and embankments in an extremely soft sludge that extended down to a depth of 10 to 15 meters (Raithel et al 2003). The differences between the predicted and measured settlements at this site are in the normal range for geotechnical structures on soft soils. Therefore, this analytical design method has been verified and is believed to represent the state-of-practice today.

The bearing behavior of the GEC is complex. 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. The more precise design procedure is based on the unit cell concept shown in Figure

6. The average vertical stress from the overlying embankment (σ_o) acts over the hexagonal area of influence of a single column unit area (A_E). This stress is equivalent to the higher stress imposed on the column ($\sigma_{v,c}$) acting over the area of the column (A_C) plus the lower vertical stress ($\sigma_{v,s}$) acting over the area of the adjacent soil ($A_E - A_C$). The difference in vertical stresses acting over the column ($\sigma_{v,c}$) due to concentration and the adjacent soil ($\sigma_{v,s}$) creates a corresponding difference in the horizontal radial stresses σ_h in the column and in the adjacent soil resulting in a ring tensile force in the geotextile. This confining tensile force in the encasement provides the missing component for the state of equilibrium. It depends not only on the horizontal stresses and their differences, but also on the strains through the ring tensile modulus J (see Section 2). In fact, this strain-dependence of the equilibrium is very specific for the system and the corresponding design procedure.

Due to this complex interactive behavior which is reflected in the design, calculation procedures are iterative and should be supported by computer software in order to attain the final equilibrium in the system. Software for calculations with the more precise method, including an incremental loading of the system and a layered soft soil, was developed by the authors. More details regarding the general possible algorithm can be found in Raithel (1999). The graphs shown in Section 6 of this paper were generated using this software.

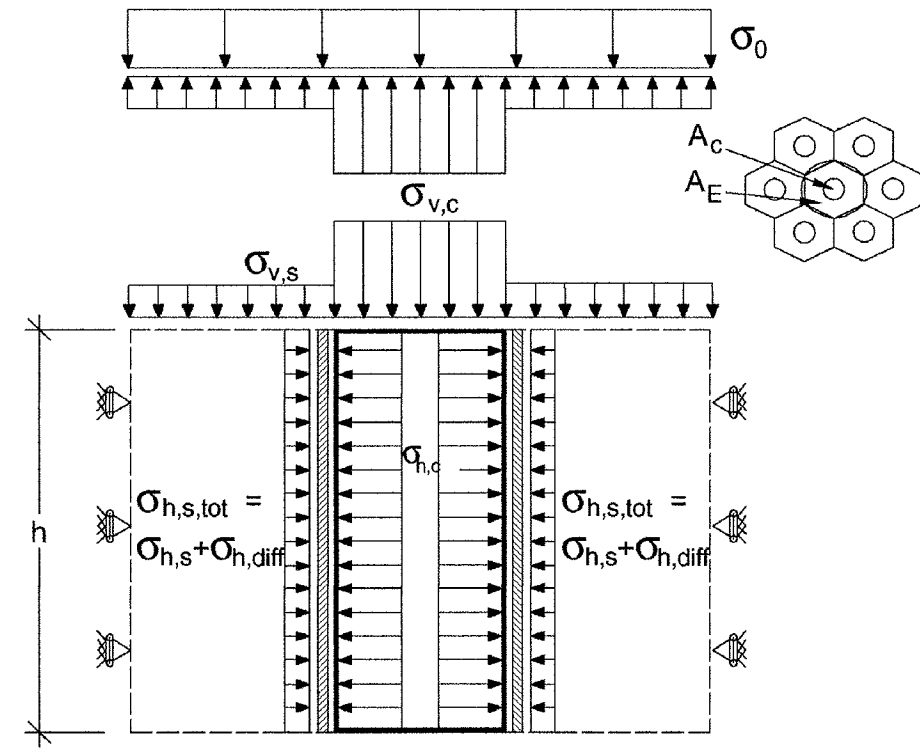


Figure 6. Analytical model for “geotextile encased columns”, simplified picture after Raithel & Kempfert (2000)

5. Geotextile encasement selection

As explained above (see Sections 2 and 4) 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 behavior. 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 a large settlement of top of GEC (i.e. of 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 (Alexiew et al 2000):

- 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 GECs 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 ring moduli from 2000 to 4000 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. More details regarding the range of polymers and strengths are presented in Alexiew, Horgan & Brokemper (2003).

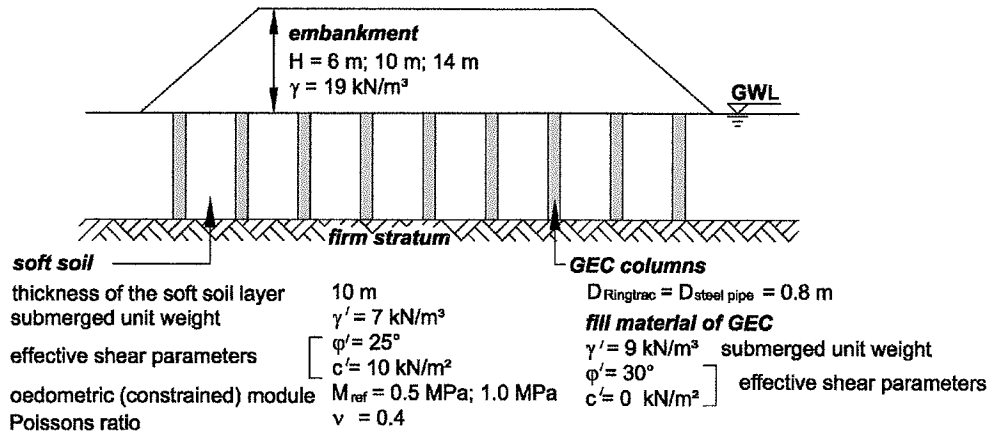


Figure 7. Overview of the system analyzed

6. Some comparative calculations and graphs

Based on the more precise analytical procedure outlined above a study was undertaken to demonstrate and compare the calculated settlements, strains etc. It focuses on the influence of two design factors, namely the ring tensile stiffness J , kN/m, and the percentage of GEC-area to total area, %. These factors can always be varied in a wide range by the design engineer. On the contrary, the choice of GEC fill is often an issue of availability, and embankment geometry, loads and soft soil parameters are fixed for a given project.

For the part of the study presented herein, the situation shown on Figure 7 was chosen. The loading consisted of 6, 10 & 14 m high embankments with a bulk unit weight, γ , equivalent to 19 kN/m^3 , constructed on homogenous foundation soil, 10 m deep. The ground water level is equal to the level of the terrain. The key deformation parameter of the soft subsoil, the oedometric (constrained) module M_{ref} , is assumed to be 0.5 MPa and 1.0 MPa for a reference stress of 100 kPa, and Poisson's ratio, ν to be 0.4. Three different "percentages" of column foundation are analyzed: 10, 15 and 20 %. Columns 800 mm in diameter are installed in the foundation soil, filled with a compacted sand with an effective angle of internal friction of $\phi' = 30^\circ$ and submerged bulk unit weight, $\gamma' = 9 \text{ kN/m}^3$. A range of tensile stiffness moduli J varying from 1000 to 4000 kN/m were analyzed, although the most common range of short- and long-term moduli of the encasement is 2000 to 4000 kN/m. The diameter of encasement is equal to the diameter of the installation steel pipe (see Section 3). The results (only in terms of settlement due to space limitation) are shown as graphs in Figures 8 and 9. They are presented with the settlement s on top of GEC on the Y-axis, the tensile modulus J on the X-axis, and the differing percentage of column area (10, 15 & 20 %), grouped on the same graph. Above each graph the embankment height and the reference oedometric (constrained) modulus M_{ref} of soft soil are cited.

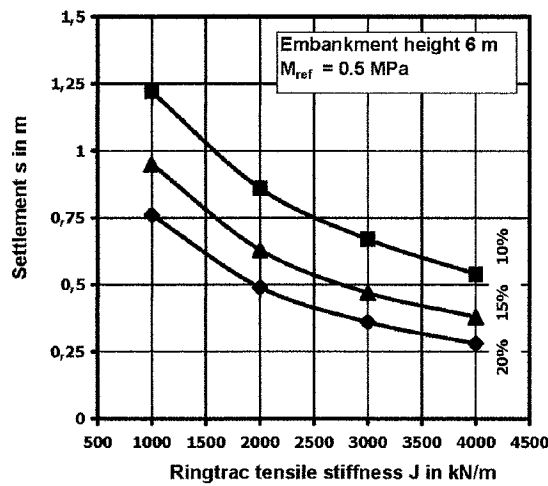
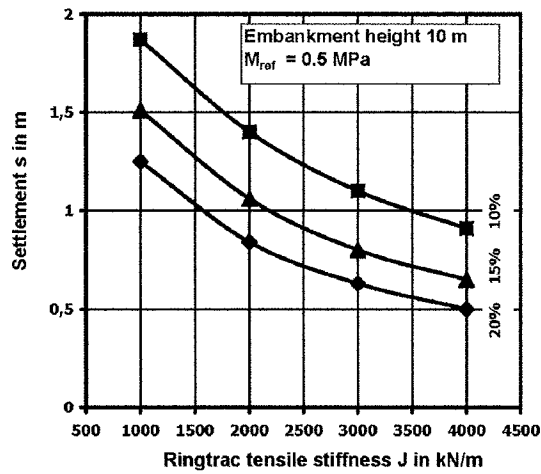
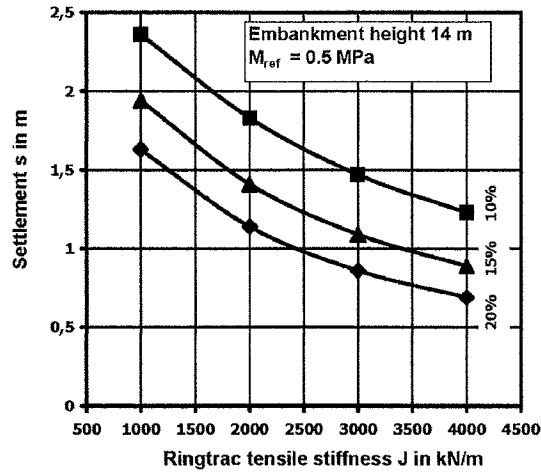


Figure 8. Settlements vs. tensile modulus of encasement for $M_{ref}=0.5 \text{ MPa}$
(NB: The modulus is time-dependent)

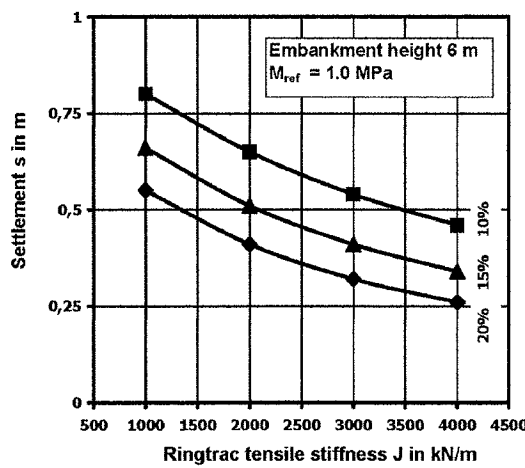
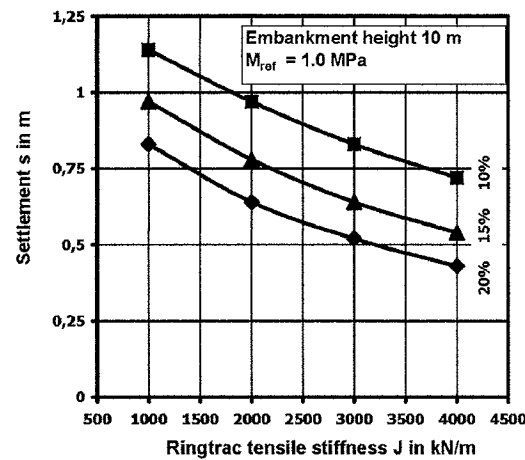
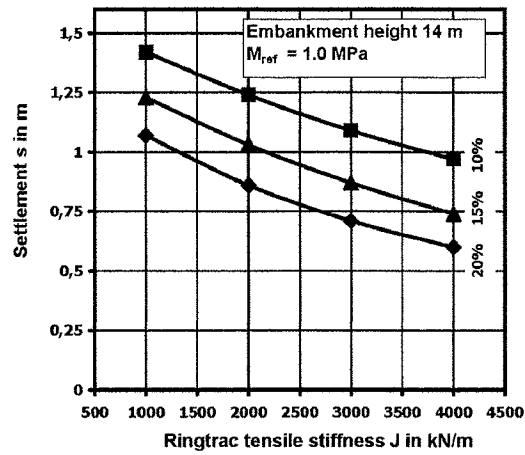


Figure 9. Settlements vs. tensile modulus of encasement for $M_{ref} = 1.0 \text{ MPa}$ (NB: The modulus is time-dependent)

In Figure 8 the cases with $M_{ref} = 0.5$ MPa are depicted, and in Figure 9 the cases for a two times stiffer subsoil with $M_{ref} = 1.0$ MPa.

Note, that for simplicity and due to the limited space not all relevant parameters have been varied, such as the diameter of GEC, the strength of soft soil, the strength of GEC fill, and the groundwater level in soft soil. The limited graphs presented are only for a preliminary orientation. They should provide an engineering feeling about the possibilities of the GEC system in the case analyzed. Note, that GECs with higher tensile moduli and /or other diameters are also available.

Nevertheless, some general tendencies can be identified. Most of them can be expected based on common engineering sense, but the graphs provide also a rough quantification.

Clearly, the role of the tensile stiffness J is very significant. For example, GECs with a ring tensile module of 4000 kN/m can reduce the settlement more than 2 times (or more than 1 meter) compared to lower moduli encasement. Analyses not shown herein result in an even stronger influence of tensile module for softer subsoils (which is not rare). On the contrary, for a subsoil with twice the stiffness the influence is in generally slightly less strong, but still very significant. The tendency can be identified comparing Figures 8 and 9. More details and graphs can be found in Alexiew, Montez & Brokemper (2003).

A combination of high tensile moduli and high percentage of GEC can reduce the settlement more than 3 times compared to low moduli and percentage. Note, that the increase of encasement tensile modulus influences the settlement more significantly than the increase of GEC percentage.

In many cases more than one combination of tensile modulus and GEC percentage can be used to achieve a required reduction of settlement. In this context, one should keep in mind, that a higher percentage of GEC leads not only to more geosynthetic material, but to a disproportionately large additional construction time and /or installation effort in terms of equipment, manpower etc. Based on the present experience, it is usually more efficient to choose higher moduli of encasement than higher percentage of columns.

The graphs allow also an estimation of the consequences of encasement creep in terms of additional creep based settlement. For that purpose, one can compare in Figures 8 and 9 the settlements for $J = J(t_2)$ and $J = J(t_1)$ (Fig. 3). The difference between these settlements is the additional settlement due to encasement creep in the time interval t_1 (e.g. end of construction) to t_2 (e.g. end of design life).

And last but not least: the GEC foundation can reduce settlements e.g. up to 3 times or up to 2 meters and more in comparison to solutions without GECs (not shown herein), and to accelerate consolidation remarkably due to the enormous drainage capacity of GECs.

7. Final remarks

The system Geotextile Encased Columns (GEC) for foundation of embankments on soft soil was developed in Germany during the last 10 years, including construction technologies, more precise and verified design procedures and corresponding high-modular low-creep encasement geosynthetics. It is an efficient alternative to traditional piles or compacted stone columns. Due to the confining encasement of the compacted sand or gravel 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 the meantime, the system has reached the stage of maturity. A wide range of high tensile-stiffness, low-creep encasements are available (Huesker 1997 - 2003). This allows an optimized design for any specific project varying the tensile moduli and the percentage area of GECs in the embankment base. Due to the use of low-creep polymers the post-construction creep-strain related settlements can be reduced to negligible levels. Many successful, highly optimized GEC projects have been designed and constructed in Europe involving various soil and construction techniques.

Simple design graphs can be employed as shown herein for preliminary estimates and for identification of tendencies including the influence of different design factors. The final design should include not only precise calculations of vertical settlement and bearing capacity based on sound geotechnical investigation and data, but also an analysis of global stability or (sometimes) numerical analyses.

Usually, a horizontal reinforcement has to be installed on top of GECs at the base of the embankment.

The general behavior of embankments on GECs is similar, but not identical to that of embankments on traditional stiff piles. The entire reinforced GEC system is as shown strongly strain -dependent, and the behavior of GECs is "softer" in relation to traditional piles. It is an interactive, ductile, self-regulating system.

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