Geotextile encased columns as foundation system: basic concepts, experience and perspective

Fundación a través de columnas encamisadas con geotextil: generalidades, experiencias y perspectivas

D. Alexiew, J. Jaramillo, D.A. Fernández, E. Ruiz

HUESKER Synthetic GmbH, Germany; Huesker Ltda. Brasil

jaramillo@huesker.de

Abstract

As foundation for Earth structures as embankments and dikes on soft soils geotextile encased columns can be used. This technology was introduced some 20 years ago and is now considered State-of-the-art in Germany and step by step worldwide. The GECs consist of compacted granular fill similar e.g. to common gravel columns with one decisive difference: they are confined in a high-strength woven geotextile "cylinder" (encasement). As a result, a structure with clearly defined parameters is constructed, whose behaviour is controlled by the geotextile encasement. Consequently, it works properly even in extremely soft soils and a wide range of fills including sand. Huge technological and design experience is available and design methods have been verified. The paper focuses in the presentation of this system in Colombia, where this kind of solution has not yet been applied. The principles and the main topics are explained. Additionally, some important conclusiones from studies are presented.

Resumen

Las Columnas Granulares Encamisadas (GEC) pueden ser utilizadas como material de fundación de terraplenes y diques sobre suelos blandos. Esta tecnología fue introducida hace un par de décadas y es considerada actualmente como un estado del arte en Alemania y paulatinamente a nivel mundial. Los sistemas con GEC´s consisten en un relleno granular compactado similar a las columnas de grava; pero con la diferencia de que el relleno se encuentra confinado dentro de un cilindro de geotextil de alta resistencia. El sistema exhibe un buen desempeño en presencia de suelos muy blandos y permite el empleo de diversos materiales (inclusive arenas) para conformar el relleno. Se ha acumulado experiencia en cuanto a las tecnologías de instalación y los métodos de diseño. Este trabajo se enfoca en presentar las GEC en Colombia, donde no se encuentran casos con este tipo de soluciones, mencionando los principios generales. Adicionalmente, se presentan las conclusiones de trabajos de investigación efectuados hasta la fecha.

1 INTRODUCTION

While looking for embankments on soft soils, generally two groups of solutions exist:

Unsupported embankments (Figure 1): there are four main options:

A. Build up embankment extremely slowly waiting for sufficient consolidation after every stage;
B. Replace the soft soil partially or totally;
C. Install a high-strength basal reinforcement providing overall and local stability and allowing building up the embankment much faster;
D. Combine the latter option with strip drains to accelerate consolidation and thus the construction process additionally.

Today only options "C" and "D" are of practical relevance in Europe. Despite all the pros and contras, the common attribute is that stability (Ultimate Limit State - ULS) can be controlled, but not the short- and long-term settlements (Serviceability Limit State - SLS).

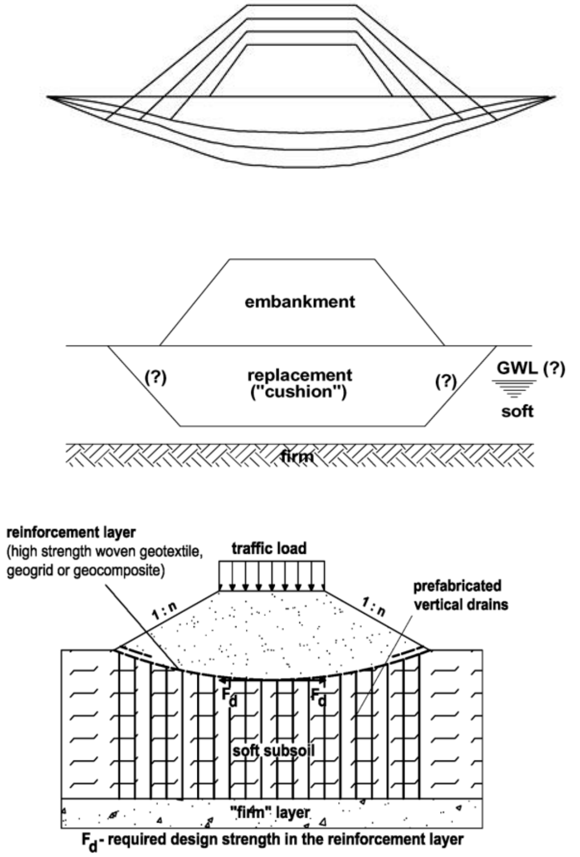

Figure 1. Unsupported embankments on soft soil: options "A", "B" and "D" from top to bottom

Supported embankments (Figure 2): the main common idea is to over-bridge the soft soil layers by supporting vertical elements of different types: rigid piles, trench walls etc. or "softer" solutions like different columns (compacted, cemented, mixed-in-place etc.). Herein the border between "pile-similar elements" and "soil improvement" seems to be fluent and depends on country, traditions etc.

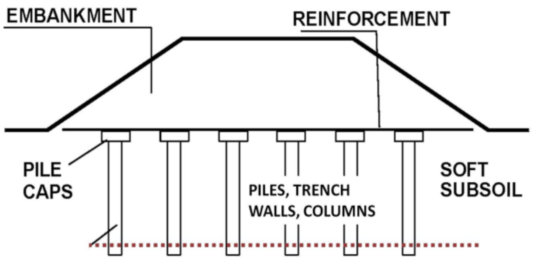

Figure 2. Supported embankments on soft soil on rigid or semi-rigid elements like piles and columns.

Twenty years ago one specific solution started: the Geotextile Encased Columns (GEC); they are discussed below in a more detailed way.

2 WHY GEC?

The development of the GEC-System started in the early 90ies, was initiated by the Contractor Möbius, Germany and developed in collaboration with Huesker Synthetic and Kempfert & Pa, Consultant.

The idea was to create a system providing:

- ♦ Versus piles:
  lower costs
  ductility (especially lateral)
  permeability
- ♦ Versus common granular columns (both in the short- and long-terms):
  mechanical stability even in extremely soft soils
  hydraulic stability
  protected from soft soil intrusion
  using finer granular materials (e.g. sand) as fill
- ♦ Versus both: lower installation energy consumption (today we call it “lower carbon footprint”).

Note: at that time execution of unbound granular columns was not allowed in Germany in soils with undrained unconsolidated shear strength SU < 15 kN/m² due to the risk of bulging during execution or later under operation; today the limit is even higher: 25 kN/m².

Using sand was from interest because it is usually available and cheaper in typical soft soil areas.

It became soon obvious that a proper geotextile encasement could help to meet the goals.

The concept is depicted in Figure 3.

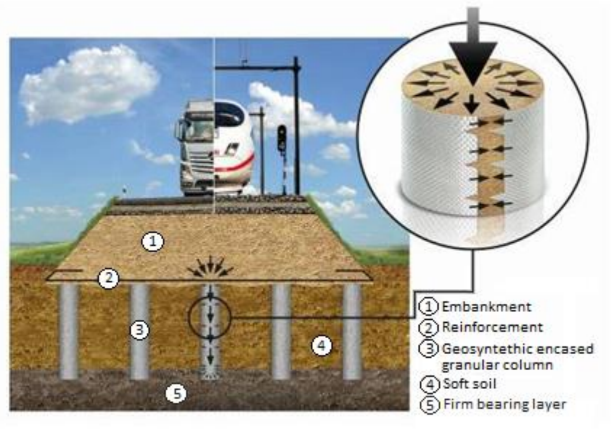

Figure 3. The GEC-System: basic overview: embankment, horizontal reinforcement (if needed), encased granular columns, soft soil, firm substratum.

3 HOW?

A “triangle” of problems had to be handled:

- ♦ A design procedure was needed for the analyses of the ULS (bearing capacity, overall).
- ♦ A proper geotextile encasement was needed to provide a sufficient lateral/radial confinement similar to a flexible oedometer (radial alias ring strength and tensile stiffness plus robustness) together with filter stability and separation capability.
- ♦ A construction procedure was needed being so far as possible quick, easy and not expensive, using common equipment and causing only a limited damage to the geotextile encasement during installation.

3.1 How to Design?

Intensive theoretical and practical research inclusive of 1:1 GEC tests and measurement programs was performed in the 90ies in Germany. A simplified design procedure had been suggested earlier in Van Impe (1989), but dealing only with the ULS aspect.

To make the long story shorter: in 2000 a proper verified design method (Raithel (1999), Raithel and Kempfert (1999), Raithel and Kempfert (2000)) was finally established and is in the meantime after small modifications included in the German Code for geosynthetic reinforced systems (EBGEO 2010 (2011)). It handles and solves in a “mixed” way both the ULS and SLS aspects (“mixed”, because it is based on a so called second order theory, say, the deformations of the GEC have influence on the stresses in the system and conversely). Main points are:

- ♦ The two stages of design (“vertical”, dealing only with the vertical behaviour of a column, and “horizontal”, dealing with the global stability of the embankment on GECs and adding a horizontal reinforcement on top of them if needed).
- ♦ The consideration of some lateral counter pressure from the surrounding soft soil on the GEC, i.e. it is an interactive model.
- ♦ The key role of the tensile stiffness of encasement in the ring alias radial direction controlling by confinement the GECs behaviour.

Assumptions, further explanations, detailed design recommendations and equations can be found in Raithel (1999), Raithel and Kempfert (1999), Raithel and Kempfert (2000), EBGEO 2010 (2011), Alexiew et al. (2005) and Alexiew et al. (2012) both for the “vertical” and “horizontal” (global) design.

3.2 How to Select the Encasement?

The confining encasement is a key component and the most substantial, decisive difference to “common” compacted granular columns (beside one other important difference: the possibility to use sand as a fill). The design asks for two parameters of it (reflecting correctly the physical reality and the common engineering sense):

- ♦ Tensile stiffness (tensile modulus J, kN/m) in “ring” direction.
- ♦ Design strength Fd, kN/m.

The leading factor is J, controlling the radial expansion of the column under load and thus its vertical compression, i.e. the settlement of its top, i.e. the settlement of embankment. Higher modulus results in less settlement. The modulus J is time-dependent due to creep and depends to 80-90% on the polymer used (Alexiew et al. (2000)) and to 10-20% on the production technology of the encasement. Due to the additional need of separation and filter stability a woven geotextile proved to be the optimal solution. To eliminate the very negative influence of joints/seams mostly on Fd, but on J as well, modern encasements are seamless textile flexible cylinders delivered to the site “flat” as a roll (Figure 4). The most established encasements today comprise two families from two different polymers, both of low creep, but with different module J and strengths F_d. Their Ultimate Tensile Strength (UTS) varies from 100 to 400 kN/m, the Ultimate Strain ε_{ult} from 10 % down to 5 % and the modulus J from 1000 to 6000 kN/m. Their typical diameters amount from 0.4 m to 0.8 m.

Figure 4. Typical woven seamless encasement as delivered to the site before installation.

Summary: today the right choice of encasement is practically not a matter of availability, but of design optimization (see below).

3.3 How to Select the Fill?

Generally a granular non-cohesive fill has to be used due to geomechanical (shear strength, low compressibility, insensitiveness to water, easier compactibility) and hydraulic (water permeability) reasons. An important difference to the "common" compacted stone/gravel columns is the possibility to use sands. Typical recommended requirements are:

- Less than 5 % of fines.
- Angle of internal friction $\varphi > 30°$.
- Coefficient of uniformity CU = 1.5 to 6.
- Coefficient of permeability k > 10-5 m/s and at least 100 times higher than k of the surrounding soil.
- Oedometric (confined) compression modulus $E_{oed} > 10 \times E_{oed}$ of surrounding soil.

In practice a wide range of materials can be used: from sands to rounded or crushed gravels and recycled materials as e.g. concrete debris (Figure 5).

Figure 5 Different fills for GEC in a field trial.

3.4 How to Optimize the System?

The goal of the design is usually to limit the settlements to a prescribed value (SLS) ensuring in the same time bearing capacity and global stability (ULS).

Under given geotechnical conditions the design engineer can vary three factors (EBGEO 2010 (2011), Alexiew et al. (2005)):

- The percentage of GECs a, % (area ratio of GEC area to total embankment foundation area); based on experience a = 10 - 20 % is recommended; diameter and/or CC-spacing of GECs can be varied.
- Fill (e.g. sand or crushed gravel).
- Ring tensile modulus J and strength of encasement.

Obviously, the higher the "a", the better the fill and the higher "J", the lower the settlements. However, the fill is often a matter of availability in an acceptable distance from the construction site; normally in problematic low land soft soil areas sands are more accessible than gravels. The diameter of GEC can depend on the commonly available equipment in a country or region (see installation issues below). The parameters of real free choice are the area ratio and the modulus/strength of encasement, the latter being also easy to transport to any place (Figure 4).

Figures 6 and 7 show an example how increasing ring tensile modulus and/or area ratio reduce the settlement (same fill is assumed).

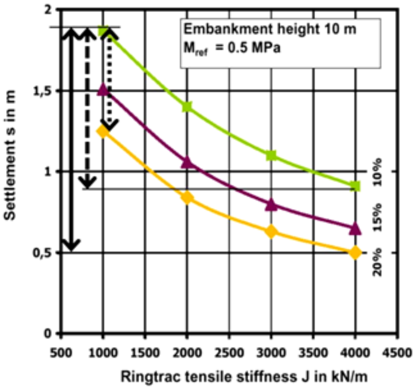

Figure 6. Achieving the same settlement by different area ratios and ring tensile modulus.

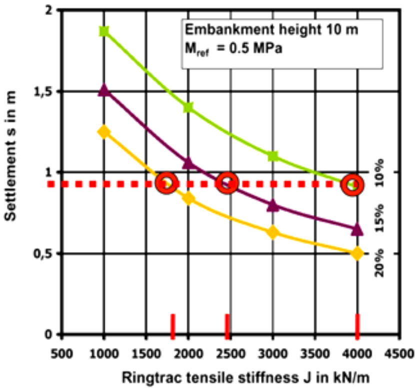

Figure 7. Reduction of settlement by increase of area ratio, ring modulus and their combination.

Further simplified graphs of similar type for a first orientation can be found in Alexiew et al. (2005).

It is usually more efficient to choose a lower percentage of GECs with higher tensile modulus J. The savings of fill material, equipment, energy, time, manpower and CO/CO2 emission are significant. In the example above (Figures. 6 &7) the increase of J from 1800 to 4000 kN/m reduces the area ratio from 20 to 10 %, it means only half the numbers of GECs need to be installed.

3.5 How to Install the GECs?

The installation technique was refined over the years, but is generally quite simple (Alexiew et al. (2012)). Drive a steel pipe down by vibration; unroll and install the encasement into the pipe; fill it; pull the pipe up by vibration; the compacted GEC is completed (Figure 8). In the case of the so called displacement method (Figure 9) the pipe is closed by flaps during driving down, and for the replacement method it is open and the local soil has to be excavated out (e.g. by a helicoidal spiral tool).

Figure 8. Examples of completed GECs: in a sand platform, in streaming water, in sludge.

It is an advantage that steel pipes are available worldwide; the flaps can be easily produced and adapted; a wide range of vibro-hammers and bearing rigs is available as well, say, finally there is nothing too specific or sophisticated. The latter makes a difference more to the majority of "common" granular columns.

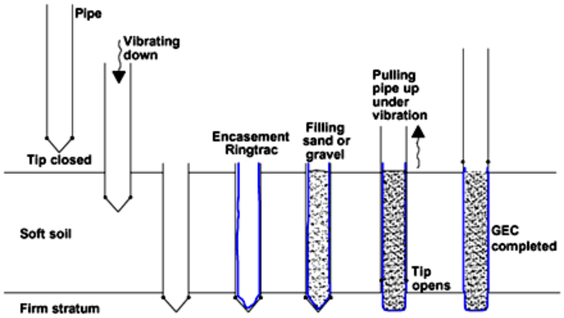

Figure 9. Scheme of the so called displacement method of installation.

How to eliminate problems in advance:

- Do not foresee a steel pipe with a too thin wall.
- Look for pipe diameters being common in a country (it starts with metric/non-metric systems).
- It is often easier to adapt the design to the pipes commonly available than the reverse (see "how to optimize the system" above); note that the modern geotextile encasements (Figure 4) can be easily customized - not so the pipes.
- Use a high-class steel for the flaps.
- Use high-frequency vibrators (> 30 Hz) with sufficient centrifugal force (> 2000 kN) and moment (> 500 Nm); resonance-free is not a must.
- The working height of the mast of rig should be at least 2 to 3 m bigger than the length of the installation pipe.
- It can be worth for larger jobs with e.g. more than 10.000 GECs to test two or three different vibrators before starting the job.
- Do not hesitate to contact a GEC-experienced professional regarding the equipment if you do not feel comfortable; it could save nerves and months of execution.

4 WHERE/WHEN GEC?

Optimal applications:

- In soft soils with a SU < 30 kN/m², even better < 20 kN/m² (possible down to SU = 2-3 kN/m²) and oedometric (confined) compression modulus E_{oed} = 0.5 -3,0 MN/m².
- For soft soil thickness of 8 to 30 m.

- For embankments, dikes, stockpiles etc. of at least 1.5 m height.
- From interest if system settlement in the range of 0.1 to say 0.5 m in the construction stage can be accepted and compensated (this is often the case); note, that because the GECs work also as "mega-drains", primary consolidation and settlements occur quickly post-construction settlements are small.
- From interest, if ductile (especially laterally) pile-similar elements being less sensitive to lateral soft soil pressure in depth are required (e.g. in the vicinity of stock piles or other directly founded loads).
- From interest as ductile active foundation elements for the loads mentioned above, reducing the lateral trust in depth mentioned also above.
- From interest in seismic areas keeping the integrity of granular columns under "shearing" seismic impact (Guler et al. (2013), Di Prisco (2006) and Die Prisco (2011)).
- From interest if a disturbance of the groundwater regime is not acceptable (they are permeable and filter-stable).
- From interest, if existing old embankments e.g. for railroads have to be upgraded for higher speeds increasing their static and even more dynamic stability (Alexiew et al. (2012), Di Prisco (2006) and Di Prisco (2011)).

5 WHAT ARE GEC FINALLY?

This is a trial to add some missing points and aspects and to create a feeling what we are talking about.

GECs are bearing pile-similar elements; it is a matter of philosophy if they should be called "piles/columns" or a "subsoil improvement system".

They are end-bearing elements. Nevertheless, due to their “softer” behaviour inclusive of the toe zone there is no need to enter the firm substratum by more than one column diameter, say by 0.5 to 0.8 m in comparison to rigid piles with some meters.

Their behaviour can be a priori controlled in a better way in comparison to non-encased granular columns due to the presence of an engineered produced in-plant element; the geotextile encasement.

They are not practically settlement-free like rigid piles, but most of the settlements occur before end of construction and can be easily compensated; however, the settlements are of other order of magnitude compared to non-supported embankments e.g. with basal reinforcement and strip drains (Figure 1).

They work additionally as vertical drains with extreme drainage capacity.

The GEC-System is ductile and to a significant extent self-regulating and robust because of the interaction of fill, encasement, soft soil and horizontal reinforcement on top of GECs (if any).

Because of their permeability and filter stability their influence on the natural hydraulic environment is marginal.

Because of their permeability and filter stability and mainly due to the installation method by vibrators (say, the installation energy is applied with a high frequency of small rates) the generated dynamic pore water overpressure is smaller and dissipates quicker, say the "disturbance" of the soft soil is limited.

The geotextile encasement works primarily as reinforcement (although in a very specific way) providing (ring) tensile forces of key importance and secondarily as separator and filter.

From a general engineering point of view the GEC-System can be positioned in terms of behavior, specifics and performance as shown in a very simplified way in Figure 10.

Figure 10. Position of the GEC System between two extrema: embankments on rigid elements and embankments without any support.

6 WHAT IS THE EXPERIENCE AVAILABLE?

In the meantime large with more than 30 significant projects and more than 2300 km of installed GECs. The most popular German design procedure ((Raithel (1999), EBGEO 2010 (2011)) seems to work properly being verified by measurement programs and practice; it may be a bit conservative (Alexiew et al. (2012), Raithel et al. (2012)); further optimization is in progress. Since about ten years it was always possible to create an optimized solution due to the huge range of geotextile encasements available today; no ULS or SLS problems known by reason of encasements. Problems arose sometimes during installation, e.g. slow installation progress; typical reasons are too light vibrators or low quality of pipe flaps, say the disrespect of basic rules.

7 WHAT ABOUT CYCLIC AND EARTHQUAKE LOADS?

7.1 Cyclic Loads

Cyclic loading can be from interest and importance due to two reasons.

First, for embankments under traffic when the cyclic impact reaches in depth the GECs. Based on German experience with embankments on soft soils a cyclic impact is of practical relevance down to ca. 4 m below a railroad and ca. 2 m below a motorway. For “thicker” embankments cyclic loads are not of practical relevance for the soft foundation soil.

Second, may be even one cycle of loading/unloading could change the GEC behaviour. This could be the case e.g. if some temporary “over-height” is being first installed on top of embankment (to accelerate consolidation if required) and later on removed to form the final gradient. Thus, a possible cyclic softening of the GECs could be critical.

Important research on this topic was performed in Italy (Di Prisco (2006) and Di Prisco (2011)).

Due to brevity no detailed comments are possible herein. However, two main findings must be mentioned:

- No softening takes place; on the contrary, the GECs become stiffer with every cycle (even after the first one) if properly encased.
- If a failure of geotextile encasement occurs under cyclic loading, this happens always at its vertical seam (Figure 11, top) being a weak zone also under long-term static loads (Alexiew et al. (2012)). (Note, that on the other hand seamless high-modulus GECs can stand even in air without lateral support, Figure 11, bottom).

Figure 11. Typical geotextile encasement failure at a seam (Di Prisco et al. (2006)) (top photo) and stand-alone in-air seamless test GECs (bottom photos)

7.2 Earthquake loads

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:

- Increased resistance to slope or soil shear failure in the event of an earthquake.
- Ultimate confinement and strengthening of the non-cohesive columns.
- 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.

- 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 (Guler et al. (2013) and Guler et al. (2014)).

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.

8 WHICH TESTS HAVE BEEN CARRIED OUT RECENTLY?

In 2011 a large scale 1:1 test of a group of GECs was performed at Berne in Northern Germany in typical soft saturated lowland soils (organic clays and peat) of about 6 to 7 m thickness. This is to our knowledge the latest 1:1 test until now. A comprehensive measurement program was installed. The GEC group consisted of 10 columns (area ratio = 12.5%, triangular pattern, center to center distance = 2.156 m, diameter = 800 mm, encasement Ringtrac® 100/100 with an UTS = 100 kN/m in ring direction). The intention was to look for possible further optimization of the present design procedures (EBGEO 2010 (2011)) and to provoke a global failure at the end of loading to check the “upper limit” of the system. For more details see Raithel et al. (2012)). The result in terms of settlements, ring tensile forces, stress concentration etc. (say the “vertical” behaviour) corresponds quite well to the design prognosis (Figure 12). However, the intended global failure did not occurred even under higher loads than the theoretical maximum. Possible explanations are higher shear strength in the confined column fill than calculated, a stronger contribution of the vertical yarns in the encasement than expected, etc (Raithel et al. (2012)). Further research is now under run incl. of 3D FEM analyses to find out the reasons for that.

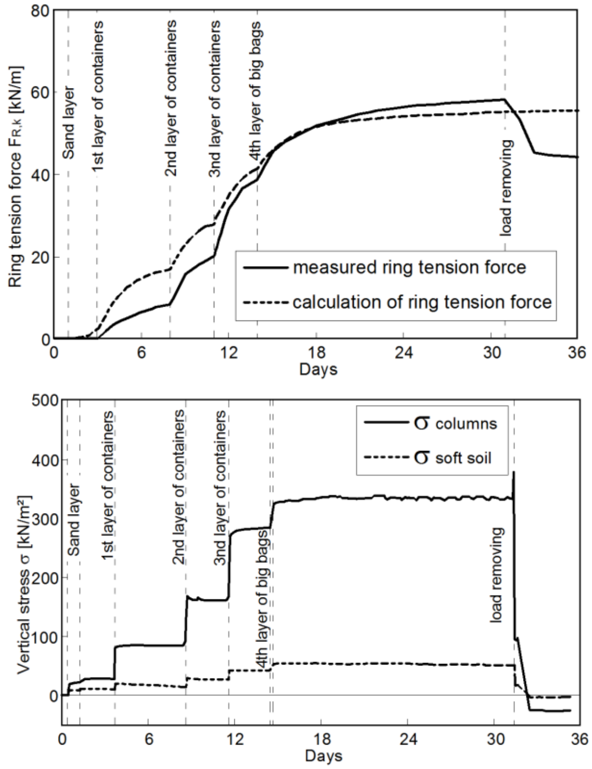

Figure 12. Large scale test Berne: Comparison of measured and calculated GEC ring tensile forces (top diagram) and

stress distribution top of GEC/soft soil in between (lower diagram)

9 HOW IS THE PERFORMANCE OF THE SYSTEM IN THE LONG TERM?

9.1 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 (Edil et al. (1994) and Krieg (2000)), 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.

9.2 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 13 & 14.

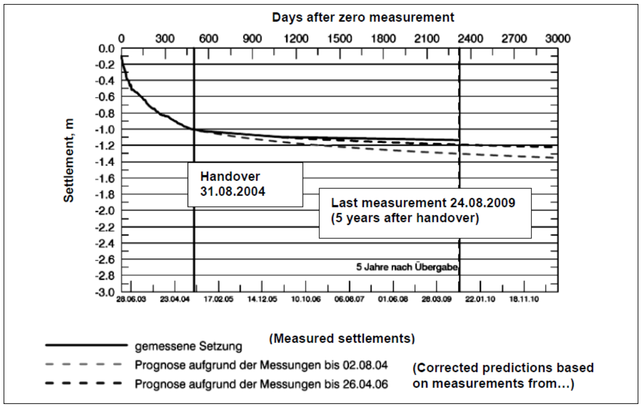

Figure 13. Results of long-term measurements and comparison with creep settlement predictions for foundation to dike enclosing extension to aircraft production site at Hamburg-Finkenwerder

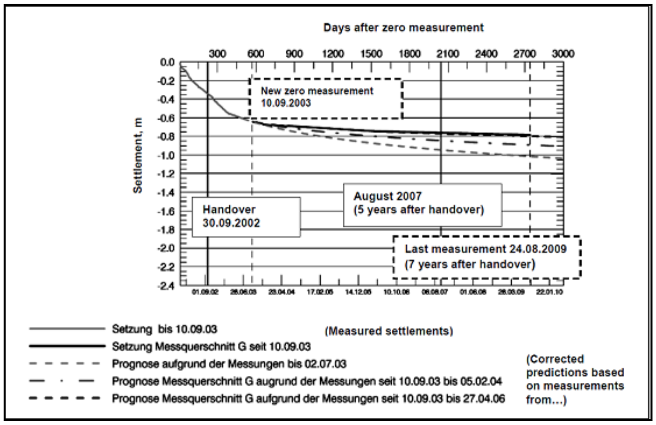

Figure 14. Results of long-term measurements and comparison with creep settlement predictions for GEC foundation to front Finkenwerder dike

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 13 and 14 indicate, a significant downward adjustment of creep settlement predictions proved necessary for both dike structures.

9.3 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 15 shows a typical time-settlement curve. Creep settlement in the order of max. 1-2 cm has been measured over the past seven years.

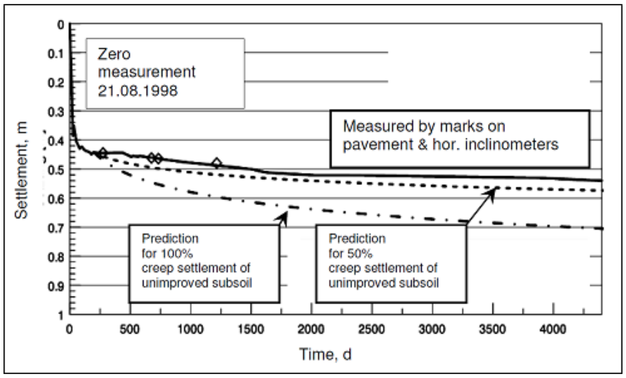

Figure 15. Time-settlements curves of representative cross-section of A 115 motorway near Saarmud

9.4 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.

10 WHAT IS THE NEED OF FURTHER RESEARCH?

Until 2002 the activities in terms of research, measurement programs, design procedures and so on were concentrated mainly in Germany. Since about 2002-2003 international theoretical and practical research, measurement programs etc became more intensive because of the increasing worldwide application of GECs and the efforts to study additional aspects and applications of the system or to optimize design. Due to brevity all the publications in this context cannot be cited herein. Useful compact overviews can be found in e.g. Tandel et al. (2012a) and Tandel et al. (2012b). Generally some basics from the late 90ies were so far confirmed (e.g. Murugesan and Rajagopal (2007)). An interesting research is under run dealing with the behaviour, possible benefits and specialized design procedures in the case of seismic impact (Guler et al. 2013).

11 ACKNOWLEDGEMENTS

Due to brevity the list of references herein include only a small part of the work done over almost twenty years in terms of executed projects, design, installation experience, research etc. by many engineers in Germany and worldwide from Brazil to Australia. They all have contributed significantly to the present State-of-the-art.

12 REFERENCES

Alexiew D, Brokemper D, Lothspeich S, (2005). "*Geotextile encased columns (GEC): Load capacity,* *geotextile selection and pre-design graphs*", Proc. Geofrontiers 2005, Austin, USA.

Alexiew D, Raithel M, Küster V, Detert O, (2012). "*15 years of experience with geotextile encased granular columns as foundation system*", Proc. Int. Symposium on Ground Improvement IS-GI, ISSMGE TC 211, Brussels.

Alexiew D, Sobolewski J, Pohlmann H, (2000).“*Projects and optimized engineering with geogrids from "non-usual" polymers*”, Proc. 2nd European Geosynthetics Conference, Bologna: 239-244.

Di Prisco C, Galli A, (2011). “*Mechanical behaviour of geo-encased sand columns: small scale experimental tests and numerical modelling*”, Geomechanics and Geoengineering, available online 01 Sep 2011.

Di Prisco C, Galli A, Cantarelli E, Bongiorno D, (2006) “*Geo-reinforced sand columns: small scale experimental tests and theoretical modelling*”, Proc. 8th Int. Conf. on Geosynthetics : 1685-1688, Yokohama, Millpress, Rotterdam.

EBGEO 2010 (2011). Recommendations for Design and Analysis of Earth Structures using Geosynthetic Reinforcements. German Geotechnical Society (DGGT), Ernst & Sohn, Essen-Berlin, 2.(the English version).

Edil T. B., Fox, P. J., Lan, L.-T. (1994). “*Stress-Induced One-Dimensional Creep of Peat. Advances in Understanding and Modelling the Mechanical Behaviour of Peat*”, Balkema, Rotterdam.

Guler E, Alexiew D, Abbaspour A, Koc M, (2013) “*Seismic performance of stone columns and geosynthetic encased columns*”, Proceedings ICEGE 2013 From case history to practice, Istanbul.

Guler E, Alexiew D, Abbaspour A, Koc M, (2014) “*Seismic performance of geosynthetic encased columns*”, Transportation Research Board 93rd Annual Meeting. Washington D.C. USA.

Krieg, S. (2000). “*Viskoses Bodenverhalten von Mudden, Seeton und Klei (Viscous Behaviour of Marine Muds, Marine and Marsh Clays)”.* Publication of Institute of Soil Mechanics and Rock Mechanics at Karlsruhe University of Technology, Volume 150.

Murugesan S, Rajagopal K, (2007). “*Model tests on geosynthetic-encased stone columns*”, Geosynthetics International, 14, No 6.

Raithel M, (1999). „*Zum Trag- und Verformungs-verhalten von geokunststoffummantelten Sandsäulen*“, Schriftenreihe Geotechnik, Heft 6, Universität Gesamthochschule Kassel, Kassel, Germany.

Raithel M, Alexiew D, Küster V, (2012). “*Loading test on a group of geotextile encased columns and analysis of the bearing and deformation behaviour and global stability*”, Proc. International Conference on Ground Improvement and Ground Control (ICGI 2012): 703-708, University of Wollongong.

Raithel M, Kempfert HG, (1999). „Bemessung von geokunststoffummantelten Sandsäulen“, Die Bautechnik (76), Heft 12, Germany.

Raithel M, Kempfert HG, (2000). “*Calculation models for dam foundations with geotextile coated sand columns*”, Proceedings of the International Conference on Geotechnical & Geological Engineering GeoEng 2000, Melbourne.

Tandel YK, Solanki CH, Desai AK, (2012), “*Reinforced granular column for deep soil stabilization: a review*”, International Journal of Civil and Structural Engineering, 2, No 3.

Tandel YK, Solanki CH, Desai AK, (2012). “*Reinforced stone column: remedial of ordinary stone column*”, International Journal of Advances in Engineering & Technology, No 6.

Van Impe W.F, (1989), *Soil improvement techniques and their evolution*, AABalkema / Rotterdam / Brookfield.