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Geotextile Encased Columns (GEC) as Pile-Similar Foundation Elements: Basics, Specifics, Case Studies

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GEOTEXTILE ENCASED COLUMNS (GEC) AS PILE-SIMILAR FOUNDATION ELEMENTS: BASICS, SPECIFICS, CASE STUDIES

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ABSTRACT

The Geotextile Encased Columns (GEC) deep foundation system for embankments and dikes on soft soils was introduced some 20 years ago and is now considered State-of-the-art in Germany, Europe and, step by step, worldwide. The GECs consist of compacted non-cohesive granular fill similar e.g. to common gravel columns with one decisive difference: they are confined in a high-strength, high-modulus, flexible geotextile "cylinder" (encasement). This engineered element with parameters being adaptable in a wide range provides a decisive tool to control and optimize the behavior of the GEC foundation system. Consequently, the GECs work properly even in extremely soft soils, and a wide range of fills inclusive of sands can be used. In the meantime vast design and technological experience is available and codified design methods exist. Initially the paper briefly describes the general idea, the basics and specifics of design, construction technology, materials, restrictions and optimal application areas. Then it focuses on three informative case studies. They are briefly presented focusing for brevity only on the most important facts and experience inclusive of the most meaningful data of short- and long-term measurement programs.

Keywords: embankment, soft soils, geotextile encased columns, design, measurements

INTRODUCTION

When considering embankments on soft soils, generally two groups of solutions exist:
Unsupported embankments; 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 much faster embankment construction;
d) combine c) with strip drains to accelerate consolidation and thus the construction process additionally (Fig. 1, left).

Today, practically only option "d" is of practical relevance. Despite all the pros and cons, the common attribute of all non-supported options is that local and overall stability (Ultimate Limit State-ULS) can be achieved and controlled, but not the short- and long-term settlements (Serviceability Limit State-SLS). The latter can be significant, e.g. up to 30% of the nominal planned embankment height.

Supported embankments (Fig. 1, right): 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 by "softer" solutions of different column types (compacted, cemented, mixed-in-place etc.). Herein the borderlines between "piles", "pile-similar elements" and "soil improvement" are fluent and depend on country, traditions, codes etc. The common attribute of the "supported" schemes is a minimized settlement.

Twenty years ago a new specific solution was launched: the Geotextile Encased Columns (GEC), which is discussed in more detail below.

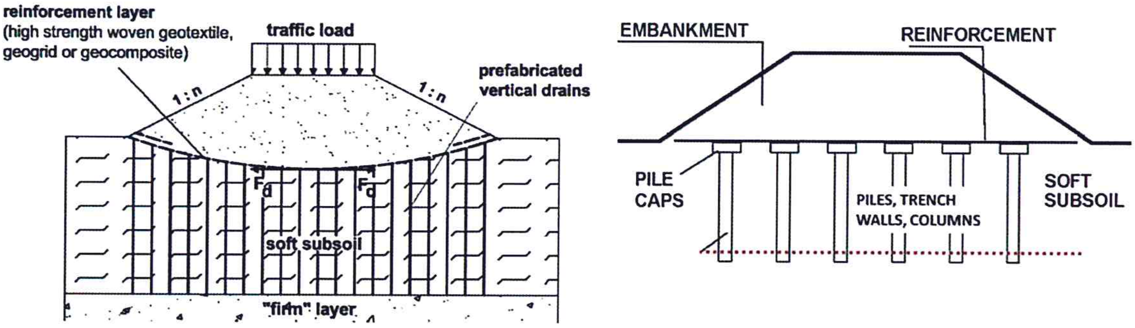

Fig. 1. Unsupported embankment on soft soil, option "d", left; supported "piled" embankment, right.

GENERAL PRINCIPLE OF GEC

The general scheme of the bearing system with Geotextile Encased Columns (GEC) is depicted in Figure 2, left. Due to the higher compression stiffness of the GECs a load concentration takes place on top of them thus reducing the stresses and compression of the soft foundation soils. The vertical load on a GEC generates also horizontal radial normal stresses outwards and radial widening of the column. This consequently provokes a counter-pressure from the surrounding soft soils <u>and</u> a confining resistance from the encasement (the latter is the key difference to "conventional" stone columns). Formulated in a simple way: it is similar to a large oedometric cell with "elastic" non-rigid walls. The mobilized confining ring tensile force F, kN/m in the encasement depends on its tensile stiffness (modulus J, kN/m) and design strength F_d, kN/m. The tensile force F and the corresponding radial strain (elongation) control the radial and consequently the vertical behavior of the GEC in terms of settlement and bearing capacity. The smaller the GEC compression, the higher the part of embankment loads taken over by them and the less the pressure on the (critical) soft soils in between.

With an appropriate encasement, the system reaches the equilibrium (total vertical stress from embankment vs. sum of stresses on top of columns <u>and</u> soft soil and radial outward stresses in the column fill vs. encasement and soft soil counter-pressures, Figure 2, right).

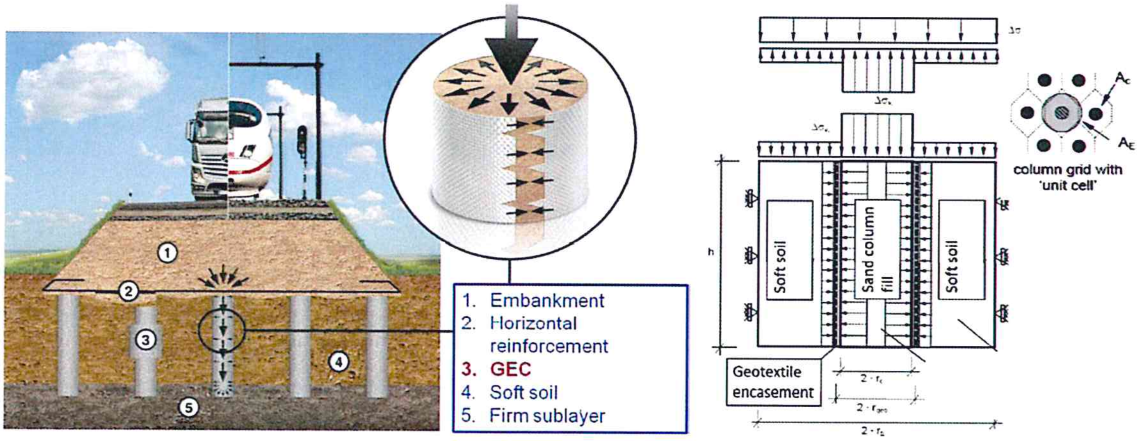

Fig. 2. General scheme of the GEC-system (left) and illustration of stresses in a "single cell" segment of the system (right)

THE BEGINNING: MOTIVATION AND FOCAL POINTS

The development of the GEC-System started in the early 1990^{ies} in Germany.
The idea was to create a system providing:

- versus piles: lower costs; ductility (especially lateral); permeability
- versus common granular columns: mechanical stability even in extremely soft soils; hydraulic stability; protection from soft soil intrusion; use of 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 unbound granular columns were not allowed in Germany in soils with undrained unconsolidated shear strength $S_U < 15$ kN/m² due to the risk of short- and long-term bulging; today the limit is even more stringent: 25 kN/m².

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

The focal points of development were:

- A sound design procedure was needed for the analyses of the ULS (bearing capacity, overall stability) and the SLS (settlements and possibly lateral embankment "spreading").
- A proper geotextile encasement was needed to provide a sufficient lateral/radial confinement (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 expansive, using common equipment and causing only a limited damage to the geotextile encasement during installation.

BASICS OF DESIGN

Very intensive theoretical and practical research inclusive of 1:1 GEC tests and measurement programs was performed in the 90^{ies} in Germany. A simplified design procedure had been suggested earlier in Van Impe (1989), but dealing only with the ULS aspect without considering strains and settlements.

A proper design method (Raithel, 1999), (Raithel & Kempfert, 1999, 2000) was developed based on the calculation model in Ghionna & Jamiolkowski (1981), verified and finally established in about 2000. After small modifications it has been included in the German Code for geosynthetic reinforced structures EBGEO (2011). It handles and solves in a "mixed" way both the ULS and SLS aspects (based on the 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 behavior of a column (Fig. 2, right, "single cell" model), and "horizontal", say "global", dealing with the global stability of the embankment on GECs and adding a horizontal reinforcement on top of them if needed (Fig. 2, left);
- 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 behavior.

Assumptions, further explanations, detailed design recommendations and equations can be found in Raithel (1999), Raithel & Kempfert (1999, 2000), Alexiew et al. (2005), EBGEO (2011), Alexiew et al. (2012), Alexiew & Thomson (2013) for both the "vertical" and "horizontal" (global) design.

GEOTEXTILE ENCASEMENT

The confining encasement is a key component and the most decisive difference to "common" compacted granular columns (beside the possibility to use sand as a fill).

The design asks for two encasement parameters: tensile stiffness (tensile modulus J, kN/m) in the "ring" direction and design strength F_d, 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 embankment. Higher modulus results in less settlement. The modulus J is time-dependent due to creep and depends 80-90% on the polymer used (Alexiew et al., 2000) and 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, modern encasements are seamless textile flexible cylinders delivered to the site "flat" as a roll (Fig. 3, left). The most established encasements today comprise two families from two different polymers, both of low creep, but with different moduli J and strengths F_d. Their ultimate tensile strength (UTS) varies typically from 100 to 400 kN/m, the ultimate strain ε_{ult} from 10 % to 5 %, the "ring" modulus J from 1000 to 6000 kN/m and the diameter from 0.4 m to 0.8 m.

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

COLUMN FILL

Generally a granular non-cohesive fill has to be used due to geomechanical and hydraulic reasons. An important difference to the "common" compacted stone/gravel columns is the possibility to use sands. Typical requirements for the fill 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. recycled concrete (Fig. 3, right).

Fig. 3. Typical woven seamless encasement as delivered to the site before installation (left) and different fills for GEC in a field trial (right).

OPTIMIZATION OF DESIGN

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 Alexiew et al. (2005), EBGEO (2011):

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

Obviously the higher the area ratio, the better the fill and the higher J, the lower the settlements. However, the fill is often a matter of availability and price; normally in problematic low land soft soil areas sands are more accessible and cheaper than gravels. The diameter of GEC can depend on the commonly available steel pipes for GEC installation in a country (see installation below). The parameters of real free choice are the area ratio and the modulus/strength of encasement, the latter being an engineered produced-in-plant and easy to transport to any place element (Fig. 4, left). Figure 4 shows an example how increasing ring tensile modulus and/or area ratio reduce the settlement (same fill is assumed). Further simplified graphs of similar type for a first orientation can be found in Alexiew et al. (2005). It is obvious that many different solutions are possible; thus the final solution is a matter of optimization.

However, it is usually more efficient to choose a lower percentage (area ratio) of GECs with higher tensile modulus J. The savings of fill material, equipment, energy, time, manpower and CO_2 emission are significant. In the example in Figure 4, left, the increase of J from 1800 to 4000 kN/m reduces the area ratio from 20 to 10 %, say the number of GECs is reduced two times (Alexiew & Thomson, 2013, 2014).

INSTALLATION OF GEC

The installation technique 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 (Fig. 4, right). In the case of the so called displacement method the pipe is closed by flaps during driving down; for the replacement method it is open and the local soil has to be excavated out (e.g. by auger). 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, so there is nothing too specific or sophisticated. The latter makes a technological difference to the majority of "common" granular columns. Important basic technological recommendations can be found in Alexiew & Thomson (2014).

FRAME OF OPTIMAL GEC APPLICATION AND SOME REMARKS

The optimal situations for the use of GECs as foundation are listed briefly below:

- in soft soils with a $S_U < 30$ kN/m², even better $S_U < 20$ kN/m² (possible down to $S_U = 2$-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;
- where system settlement in the range of 0.1 to e.g. 0.5 m in the construction stage can be accepted and compensated (this is often the case); because the GECs work also as "mega-drains", primary consolidation and settlements occur quickly; post-construction settlements are small;
- where ductile laterally resistant (shearing/bending) pile-similar elements are needed due to lateral soft soil pressure in depth e.g. in the vicinity of stock piles or embankments (Raithel et al., 2005, Alexiew et al., 2010);
- where ductile active foundation elements working as lateral pressure relief are needed (Schnaid et al., 2014);
- of note in seismic areas due to ductility (see above) and assured integrity of granular columns due to encasement under seismic impact (Guler et al., 2013, 2014);
- of note under cyclic loads (e.g. upgrading existing old railroad embankments for higher speeds and/or higher loads) increasing not only their static but even more their dynamic stability demonstrating integrity and stiffening (Nods & Brok,2003, Di Prisco et al., 2006, Di Prisco & Galli, 2011, Alexiew et al., 2012);
- where a disturbance of the groundwater regime is not acceptable (they are permeable and filter-stable);

Some remarks:
Comments on the general position of the GEC foundation system in relation to unsupported embankments and embankments e.g. on rigid piles (Fig. 1, right) can be found in Alexiew & Thomson (2014). For a list of main projects and an overview of research done as per 2011 see Tandel et al. (2012a, 2012b). We recommend to the interested reader e.g. Murugesan & Rajagopal (2007). The experience of any type is huge after 20 years with more than 30 significant projects and more than 2300 km of installed GECs. Further projects are under execution. Research on some special topics (e.g. earthquake) is under way (Alexiew & Thomson, 2014).

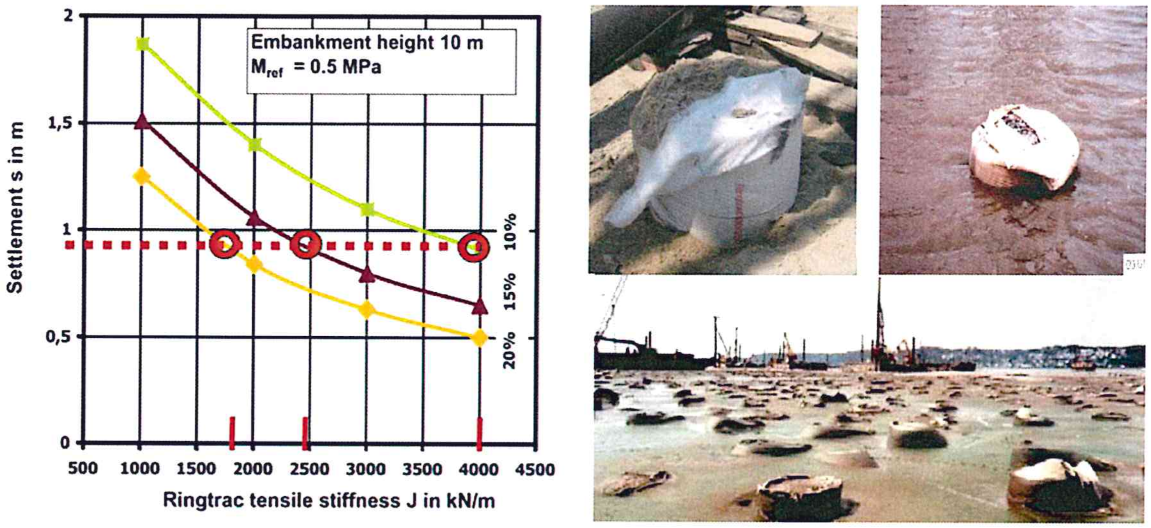

Fig. 4. Same settlement by different area ratios and ring tensile modulus of encasement (left) and examples of completed GECs: in a sand platform, in streaming water, in sludge (right).

SOME CASE STUDIES

Extension of Airbus site at "Mühlenberger Loch", Hamburg, Germany, 2000-2002

The plant site of Airbus (EADS) in Hamburg-Finkenwerder at the river Elbe was enlarged by 140 ha in particular for the production of the new Airbus A 380. The land reclamation was carried out by enclosing an area of extremely soft soils (sludge) with tidal changes by a 2.4 km long dyke. The soft soil thickness with undrained shear strength S_U of only 0.4 to 10.0 kN/m² varied from 8 to 14 meters. Under these conditions a "non-supported" solution of any type (see "a" to "d" in Introduction) was not of practical interest. The dyke was founded on about 60,000 geotextile-encased sand columns of corresponding length with a diameter of 0.8 m and a total installed length of about 650 km. It is until today the biggest single GEC job executed. The GECs were installed in about a year. A typical cross section with the GECs can be seen in Fig. 5. More detailed information can be found in Raithel et al. (2002), Alexiew & Raithel (2015). Figure 6 shows typical dyke settlements over more than 10 years including both primary and secondary (creep) consolidation. Creep settlement predictions had to be revised two times to fit reality: the settlements were again and again smaller than predicted. Between the 5th and the 10th year after handover the secondary settlement is about 0.2 m under a dyke of 9 m height. After 10 years the rate of creep settlements tends to zero. It seems that GEC foundations achieve an approx. 50% - 75% reduction in creep settlement. This comparison is based on rough estimations and calculations; precise e.g. time-dependent analysis for a "non-supported" dyke has been never done (see above).

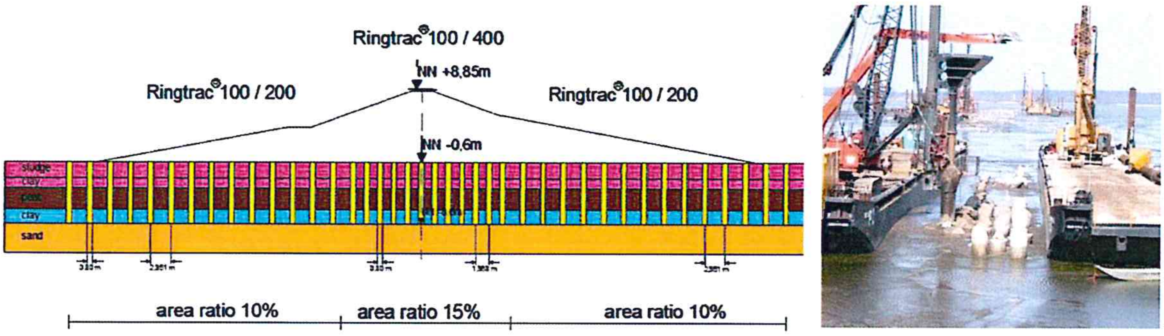

Fig. 5. Typical dyke cross-section at Airbus site Hamburg (left) and GEC installation (right).

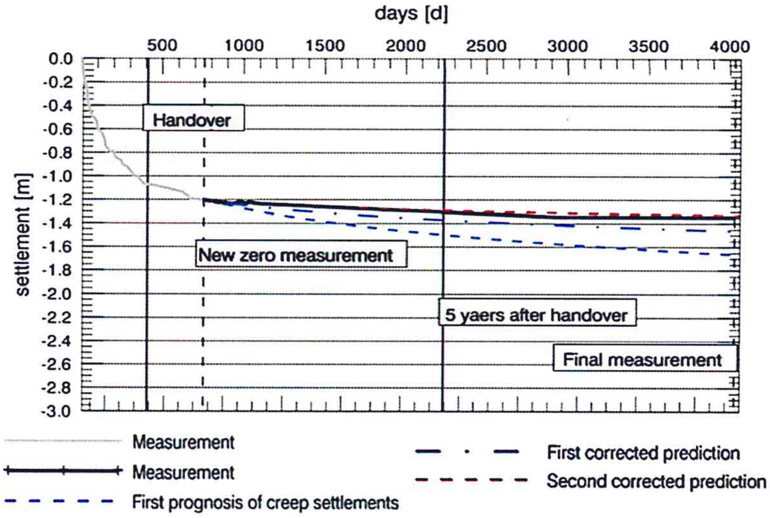

Fig. 6. Long-term settlements over more than 10 years: creep settlements are significantly lower than predicted.

High-speed rail link (HSL) Paris-Amsterdam at Westrick, Netherlands, 2002

Near Breda the new high-speed railroad from Paris to Amsterdam had to cross the former waste disposal Westrick from km 42.6 to km 42.8. The landfill Westrick is an old sandpit which was filled from 1947 to 1959 with unsorted uncompacted municipal and industrial waste. The waste thickness is in the range of 4 to 6 m followed by sands with some thin clay interlayers (Fig. 7). All materials demonstrated a significant degree of contamination with oil, PAC and heavy metals. The pH varied from 9.0 to 10.5, say to strongly alkaline. On the one hand the design was relatively conservative in terms of GEC replacement ratio and strength due to the settlement limitations, the extreme inhomogeneity of waste and the high chemical impact. On the other hand due to economic reasons no GECs at all were installed below the shoulders of embankment outside a load spreading zone below the tracks (Fig. 7, left). The GECs had a diameter of 0.8 m with an average replacement ratio of 15 % and a "ring" UTS of 300 and 400 kN/m. They were produced from Polyvinylalcohol (PVA) due to two reasons: the high chemical resistance in a wide range of media and the high ring tensile modulus in the short- and long-term (after creep) ensuring a more efficient reduction of settlements (absolute and differential). Totally about 2200 GECs were installed in June and July 2002 using sand as fill. The displacement method was applied successfully despite the problematic character of waste. The productivity varied from 40 to 80 GECs per day depending on the local resistance of waste. For more details see Nods & Brok (2003). In Figure 7, right, typical settlements are depicted. In the GEC-supported zone they amount to 0.08 m between start of construction (July) and end of August. Important: they are practically equal across the embankment. After August, no more settlements occur. The settlements of the non-supported shoulder are three times the GEC supported zone although the average load is one half.

Regarding the project at Westrick some specific issues are worth to be kept in mind: GECs can be installed even in such a problematic "subsoil" as heterogeneous waste, both absolute and differential settlements can be controlled; the latter was a specific hardly predictable aspect in this case.

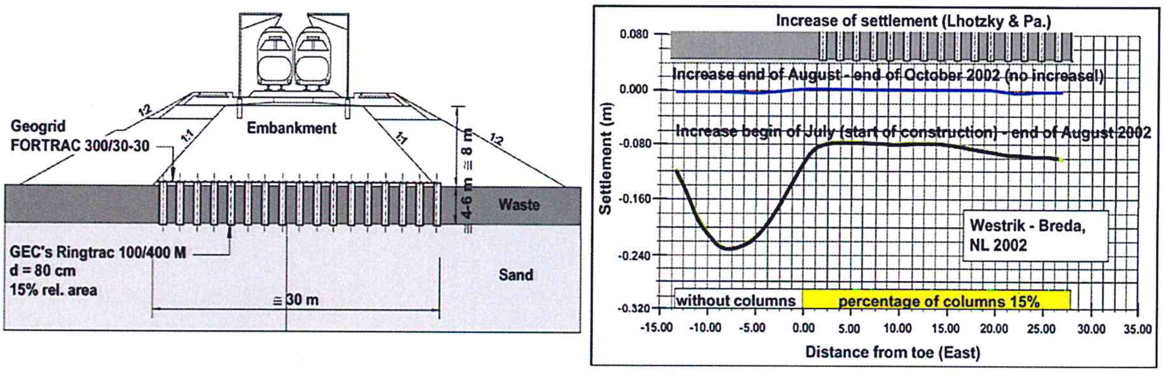

Fig. 7. Typical railroad cross-section at Westrick (left); increase of settlements for two periods (right).

A2 Motorway embankment, Jordanovo, Poland, 2010-2011

The first State-of-the-Art application of GEC in Poland was carried out in 2010-2011 during the construction of the Motorway A2. The subsoil consists of peat in the uppermost 5 m, followed by the so-called 'gyttja' (sensitive problematic clay). The thickness of the soft soil varies extremely along the embankment axis with a maximum of about 28 m (Fig. 8, left). The GEC system was designed and executed with 0.80 m diameter columns in a triangle pattern (axial spacing 1.97 m, area ratio15 %, total number of columns 3,400). The length of GECs amounts to more than 29 m: the longest ones executed until today.

A heavy rig with a ring vibrator was used. Figure 8, right, shows the corresponding settlements starting with the first stages of construction. As usual most of them occur quite quickly. Extrapolation of data resulted in the conclusion, that the stringent long-term settlement limitations for the A2 will be met. More details about the project can be found in Küster et al. (2012).

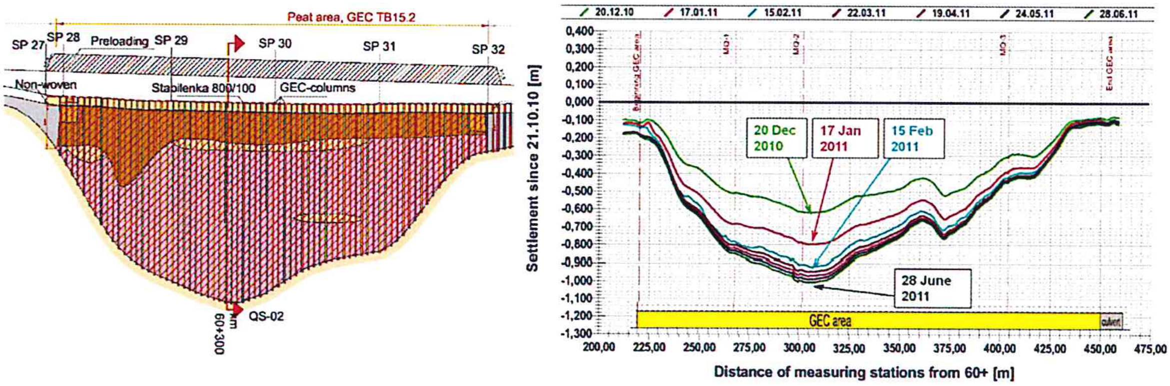

Fig. 8. Typical railroad cross-section at Westrick (left); increase of settlements for two periods (right).

FINAL REMARKS AND ACKNOWLEDGEMENTS

Due to space reasons neither more case studies nor corresponding details can be included herein. They can be found e.g. in Kempfert (1996), Kempfert & Raithel (2002), De Mello et al. (2008), Alexiew et al. (2010), Raithel et al. (2012), Schnaid et al. (2014), Alexiew & Raithel (2015). The GEC foundation system has reached the stage of maturity. Projects have been successfully executed worldwide. At least one verified and codified design procedure is available (EBGEO 2011) (may be a bit conservative overestimating sometimes settlements and underestimating global stability) and two approved by practice installation options are established as well. Installation techniques and equipment are quite simple and accessible for everyone, GEC lengths of up to 29 m have been installed and it seems to be not the limit. A wide range of non-cohesive fills can be used including sand (in fact the most used fill until today); the latter can be a significant advantage e.g. in lowlands and/or on seashores, where other fills are rare or expensive. A wide range of geotextile seamless encasements from two polymers and with diameters from 0.4 to 1.0 m is available. They are easy to transport made-in-plant engineered controlled elements. Consequently an optimized solution is possible whatever the project circumstances are.

In all the projects completed herein many competent colleagues (designers, owners, supervisors, installers etc.) have been active, flexible and enthusiastic. Their successful efforts are strongly appreciated.

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