

Geotextile-Encased Columns - a foundation system for earth structures, illustrated by a dyke project for a works extension in Hamburg

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Abstract: The foundation system GEC has been developed and used since 1995 for founding earth structures on low-bearing soils. For the Airbus works enlargement by 160 ha into the tidal mud flats of the Elbe River in Hamburg (2001/2002), over 60 000 geotextile-encased columns were installed to found a dyke on organic soils. The theoretical background of the GEC bearing system is explained with the help of this project. The processes both for the design and the preparation of the earth statical calculations are presented. Taking into consideration the special boundary conditions of the project (tidal influence, inaccessible sediment in the river bed, very limited construction time), the main steps of GEC installation are explained.

1 INTRODUCTION

The foundation system ‘Geotextile-Encased Columns’ (GEC) is a further development of well-known column foundations such as vibro displacement piles and granular piles. In contrast to conventional column foundations, encased columns can also be used as a ground improvement and bearing system in very soft soils, for example peat or sludge (undrained shear strength $c_u < 5 \text{ kN/m}^2$).

The plant site of the Airbus Company in Hamburg-Finkenwerder was enlarged by approx. 140 ha for new branches of production, in particular for the production of the new Airbus A 380. The area extension was carried out by enclosing the polder (marsh or wetland) with a 2,4 km long dyke. In this area, the thickness of the soft soil layer is between 8 and 14 m. The undrained shear strength c_u of the soft soil is between 0.4 and 10.0 kN/m². Further details are shown in Kempfert & Raithel (2002) and Lindmark & Küster (2004).

The necessary dyke foundation was realized using about 60000 geotextile-encased sand columns with a diameter of 80 cm, which were sunk to the bearing layers at depths of between 4 and 14 m below the base of the dyke.

Due to the foundation system the dyke could be constructed on the subsoil with very little shear strength and high deformability in a construction time of approx. 9 months.

2 BEARING SYSTEM GEC[®] AND CALCULATION MODEL

2.1 Bearing System GEC[®]

As opposed to conventional stone column foundations, geotextile-encased sand or gravel columns can be used as a ground improvement method for very soft soils. With a non-encased column, the horizontal support of the soft soil must be equal to the horizontal pressure in the column. With a geotextile-encased column, the horizontal support of the soft soil can be much lower, due to the radial supporting effect of the geotextile casing. The horizontal support depends also on the vertical pressure over the soft soil, which can be much smaller. As a result we get a stress concentration above the column head and a lower vertical pressure over the soft soil and therefore a large settlement reduction. To withstand the high ring tension forces, these geotextile casings are manufactured seamlessly. The columns act simultaneously as vertical drains, but the main effect is the transport of the load to a deeper bearing layer.

To assess the effectiveness (β = settlement without/with columns) the encased columns in relation to conventional column foundations, the results of tests according to Raithel (1999) and executed projects are compared with published results of stone column foundations (Fig. 1), see also Kempfert (2003).

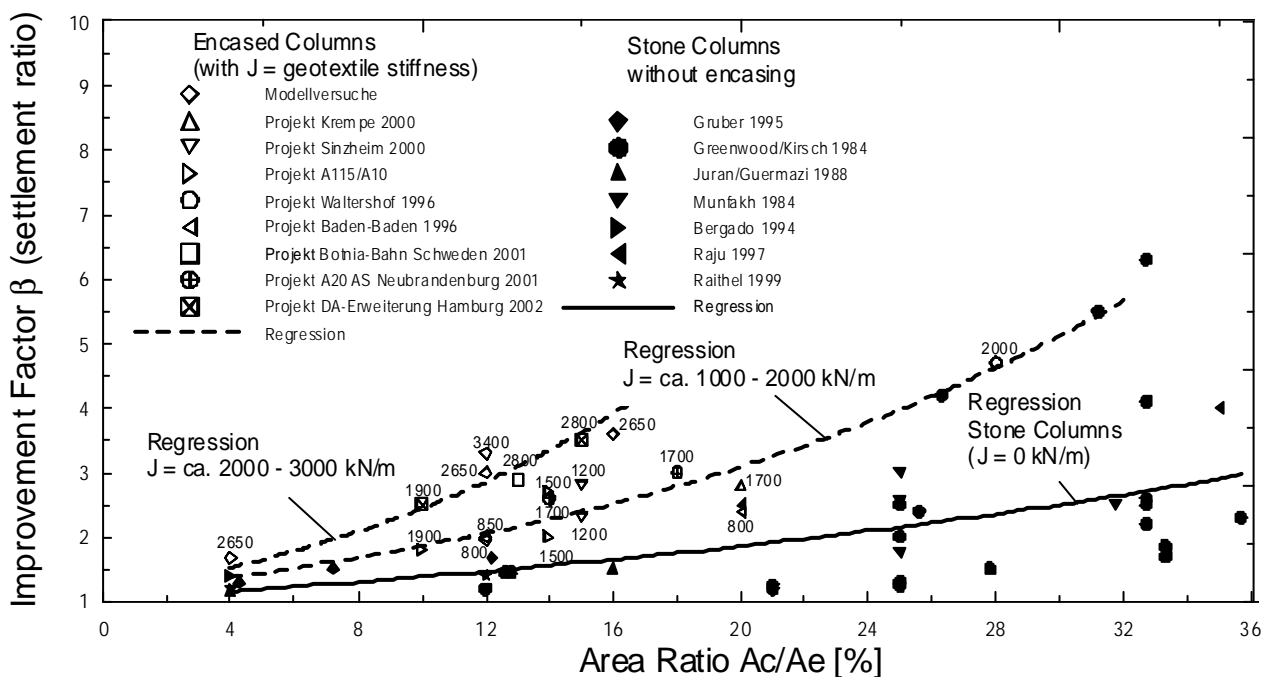


Figure 1 Soil improvement factors depending on area replacement ratio

The GEC are arranged in a regular column grid. Based on the unit cell concept, a single column in a virtual infinite column grid can be considered. A_C designates the column area. A_E is the influence area of a hexagonal element of a single column in triangular grid, which can be transformed into a circular element with an equivalent area, see Figure 1.

2.2 Numerical calculation using FEM

For the numerical calculation of the GEC-System, the program PLAXIS (Finite Element Code for Soil and Rock Analyses) was used. An advantage of this program is the possibility to use several soil models. For the soft soil, the Soft Soil Model (SSM), a model of the Cam-Clay type, was used. For the sand and gravel of the column material, the Hard Soil Model (HSM), a modified model on the basis of the Duncan/Chang model, was used.

The calculation of the bearing and deformation behaviour leads to a three-dimensional problem. In practice a three-dimensional calculation model is hardly used. Therefore, in the numerical analysis the problem can be simplified and the calculation can be split into two separate models. By the examination of a single column (according to the 'unit cell concept' as shown in Fig. 2) and the use of an axial symmetric calculation model, the ring tension forces for the design are determined. To investigate the deformation behaviour of the whole system, for example an embankment foundation, a cross section model (plane strain model) is used. The casing cannot be simulated directly, because the columns must be substituted by walls of equal area ratio. Therefore, a substitute shear parameter is defined, which is used for the column material after activation of ring tension forces. The definition and derivation of the substitute shear parameters are shown in Raithel (1999).

2.3 Analytical Calculation model

Generally, an analytical, axial symmetric model according to Raithel (1999) and Raithel & Kempfert (2000) is used for calculating and designing a geotextile-encased column foundation, see Figure 2. The model was developed on the basis of the conventional calculation models used for granular piles, which are completed by the effect of the geotextile casing. Apart from the boundary conditions in Figure 2 the following assumptions were made:

- The settlements on the top of the column and the soft soil are equal.
- The settlement of the bearing layer below the columns can be neglected.
- In the column the coefficient of active earth pressure $K_{a,c}$ applies.

- Using the excavation method (see chapter 4), the earth pressure at rest with $K_s = K_{0,s} = 1 - \sin\phi$ is valid; if the displacement method (see chapter 4) is used, an enlarged coefficient of earth pressure $K_s = K_{0,s}^*$ is given before loading.
- The geotextile casing has a linear-elastic material behaviour (stiffness J).
- For design of the foundation the drained (end) condition is decisive, because then the maximum settlements and ring tension forces are reached.

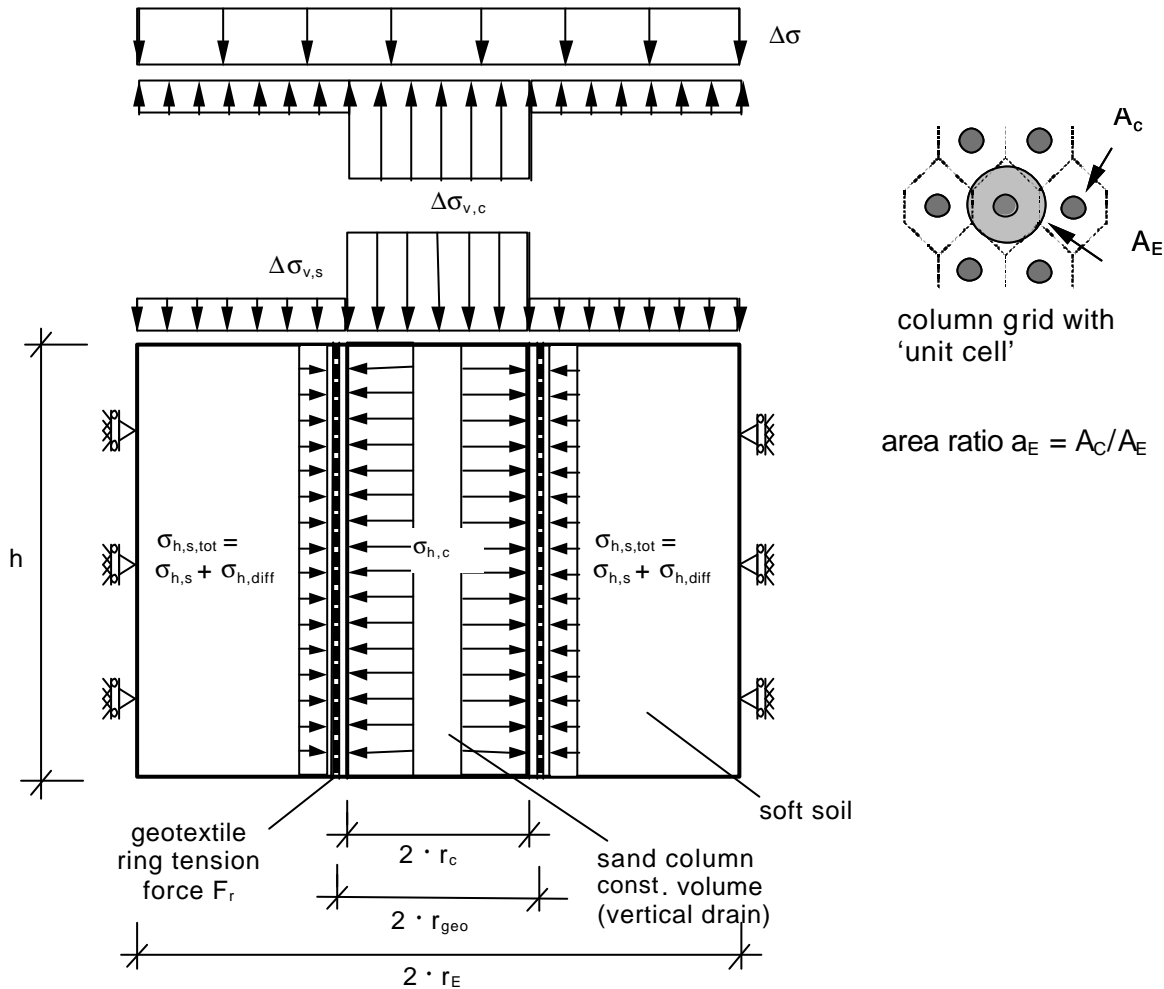


Figure 2 Calculation model 'geotextile encased column'

As shown in Figure 2, there is an additional horizontal stress in the column $\Delta\sigma_{h,c}$ (index h = horizontal) due to the additional vertical stress $\Delta\sigma_{v,c}$ (index v = vertical) over the column head. In view of the equilibrium between the additional loading $\Delta\sigma$ and the corresponding vertical stresses over 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. $\sigma_{v,0,c}$ and $\sigma_{v,0,s}$ are the initial vertical stresses in the column and the soil (if the excavation method is used, $K_{0,s}^*$ must be substituted by $K_{0,s}$):

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

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

The geotextile casing (radius r_{geo}) has an linear-elastic behaviour (stiffness J), whereby the ring tensile force F_R can be transformed into a horizontal stress $\sigma_{h,geo}$, which is assigned to the 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_c and the settlement of the soft soil s_s (oedometric modulus $E_{oed,s}$, poisson ratio ν_s) are calculated according to Ghionna & Jamiolkowski (1981). Assuming equal settlements of column s_c and soft soil s_s , the following calculation equation can be derived:

$$\left\{ \frac{\Delta\sigma_{v,s}}{E_{oed,s}} - \frac{2}{E^*} \cdot \frac{\nu_s}{1-\nu_s} \left[K_{a,c} \cdot \left(\frac{1}{a_E} \cdot \Delta\sigma - \frac{1-a_E}{a_E} \cdot \Delta\sigma_{v,s} + \sigma_{v,0,c} \right) - K_{0,s} \cdot \Delta\sigma_{v,s} - K_{0,s}^* \cdot \sigma_{v,0,s} + \frac{(r_{geo} - r_c) \cdot J}{r_{geo}^2} - \frac{\Delta r_c \cdot J}{r_{geo}^2} \right] \right\} \cdot h = \left[1 - \frac{r_c^2}{(r_c + \Delta r_c)^2} \right] \cdot h \quad (6)$$

$$\Delta r_c = \frac{K_{a,c} \cdot \left(\frac{1}{a_E} \cdot \Delta\sigma - \frac{1-a_E}{a_E} \cdot \Delta\sigma_{v,s} + \sigma_{v,0,c} \right) - K_{0,s} \cdot \Delta\sigma_{v,s} - K_{0,s}^* \cdot \sigma_{v,0,s} + \frac{(r_{geo} - r_c) \cdot J}{r_{geo}^2}}{\frac{E^*}{(1/a_E - 1) \cdot r_c} + \frac{J}{r_{geo}^2}} \quad (7)$$

$$\text{with } E^* = \left(\frac{1}{1-\nu_s} + \frac{1}{1+\nu_s} \cdot \frac{1}{a_E} \right) \cdot \frac{(1+\nu_s) \cdot (1-2\nu_s)}{(1-\nu_s)} \cdot E_{oed,s} \quad (8)$$

This equation can be solved by iterative procedure. The oedometric modulus $E_{\text{oed},s}$ of the soil should be introduced stress dependent. More details are shown in Raithel (1999) and also in Raithel & Kempfert (2000).

3 CALCULATION RESULTS

On the basis of the above-described analytical calculation model and additional FEM-calculations for different parts of the dyke, the grids in Table 1 were designed with more than 60000 columns using different types of casing, called Ringtrac.

The stiffness of the geotextile casing was between $J = 1700$ and 2800 kN/m. The maximum high tensile force of the geotextile varied between 100 and 400 kN/m over the cross section of the dyke. The length of the columns depended on the depth of the soft soil along the dyke line, which varied between 4 and 14 m.

For this project, the ratio of the column area A_C to the influence area A_E (A_C/A_E) was between 0.10 and $0.20 = 10\%$ to 20% .

As a result of the stability calculations, a geocomposite with a high tensile strength (maximum high tensile force 500-1000 kN/m) in the dyke base, perpendicular to the dyke centerline is needed, to accelerate the construction of the dyke and to obtain a high degree of stability in the initial stage of construction. It was also necessary to increase the stability if the area behind the dyke was to be raised to a height of 5 to 8 m above sea level. The factor β ($\beta = \text{settlement without GEC} / \text{settlement with GEC}$) of ground improvement in soft soil amounts to about $\beta = 2.5$ to 4. The main calculation results for the design of the dyke foundation are shown in Table 1 and as an example in Figure 3.

Table 1 Calculation results

Dyke-section	Part	Height [m MSL]	Grid A_C/A_E [%]	approx. no. of columns	Settlement [cm]
II	middle	+9,25	17	04.400	50
	side	+5,50	10		47
III	middle	+8,90	15	05.700	41
	side	+5,50	10		39
IV	middle	+8,90	15	08.000	70
	side	+5,50	10		65
V	middle	+8,90	15	17.000	109
	side	+5,50	10		106
VI	middle	+8,90	15	12.000	95
	side	+5,50	10		88
VII	middle	+8,90	20	09.800	169
	side	+5,50	15		146

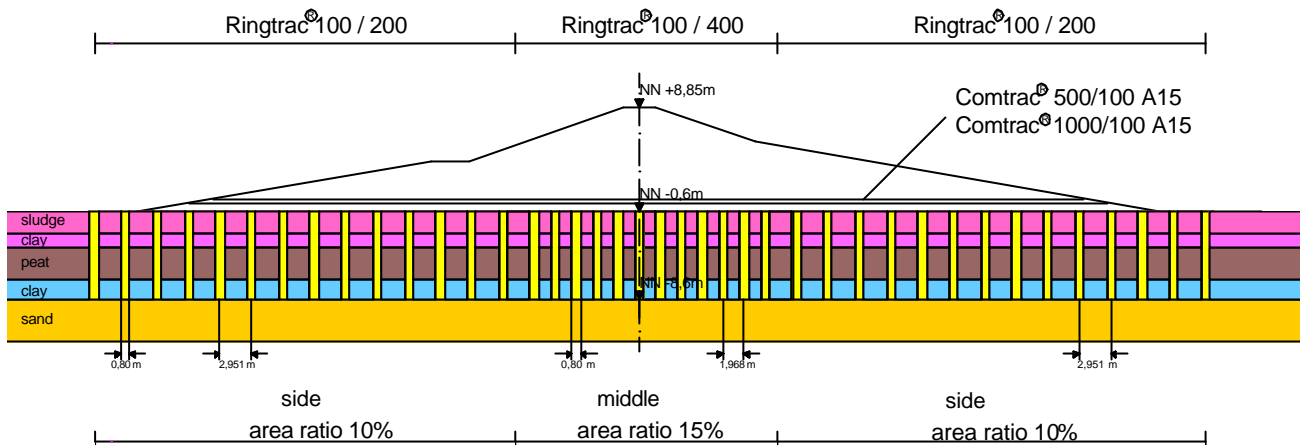


Figure 3 Cross section (for example in section VI)

4 GEOTEXTILE-ENCASED COLUMN INSTALLATION

Normally, there are two installation methods in practice. With the excavation method, an open steel pipe is driven to the natural foundation and its contents are removed by soil auger. With both economy and ecology in mind, the vibro displacement was used for the entire Hamburg project. A steel pipe with two base flaps (which close upon contact with the soil) is vibrated down to the bearing layer, displacing the soft soil.

The majority of the columns was installed using equipment operating from offshore pontoons (110×11 m) to better contend with tidal fluctuation (3.5 m water level difference). At low tide, work continued with the pontoons resting directly on the soft soil, as shown in Figure 4. After installation, the column heads were stabilized by filling sand between the columns. Notably, no tidal erosion was observed.



Figure 4 Installation from offshore pontoon and column after drawing

A further GEC[®] construction method was used for numerous road and railway projects in Germany, the Netherlands and Sweden.

The vibro displacement machine stood on top of the installed columns, with mats under the 120-ton unit to facilitate load distribution. This land construction method is shown in Figure 5. Figure 5 also shows the finished dyke.



Figure 5 The well-tested vibro displacement method on land and the finished dyke

5 MEASUREMENTS

Due to the different soil conditions along the dyke length 7 measurement cross sections are necessary.

In a typical measurement cross section, 4 groups are placed, each containing one earth pressure gauge and one water pressure gauge above the soft soil layer, and two piezometers within the soft soil. In each cross section, one horizontal and two vertical inclinometers are used for the examination of the deformation behaviour.

On the basis of the measurements, it can be shown that the real soil conditions are better than the soil parameters in the tender documents, especially with regard to the consolidation behaviour, see also Raithel et al. (2002).

Due to the high effectiveness of the foundation system, the dyke could be constructed in approx. 9 months to a height of about 7 m. Therefore, after 39 weeks, the necessary protection against flooding was attained.

The measuring data on the settlements in dyke section VI are shown in Figure 6.

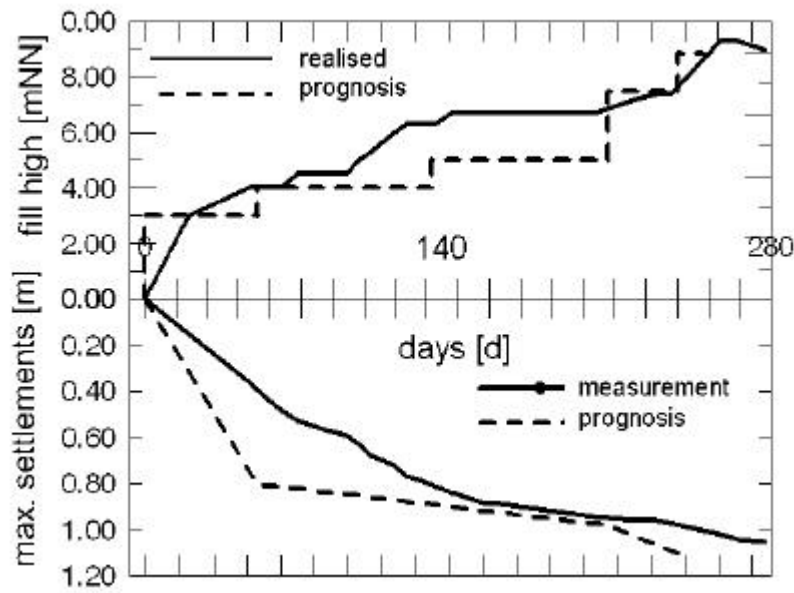


Figure 6: Measured settlements, for example in section VI

6 SUMMARY

On soft organic soils underlain by bearing layers in reachable depths, the foundation system ‘Geotextile-Encased Columns’ makes it possible to build safe and flexible foundations with low settlements due to enormous settlement reduction, acceleration of settlements and increase of the shear strength. In this contribution, numerical and analytical models for calculation and design of the foundation system ‘geotextile coated sand columns’ were reflected.

The factory site of the Airbus Company in Hamburg-Finkenwerder was enlarged by approx. 140 ha. The area extension was carried out by enclosing the polder with a 2.4 km long dyke.

The necessary dyke foundation was realized using about 60 000 geotextile-encased sand columns (GEC[®], Möbius System) with a diameter of 80 cm, which were sunk to the bearing layers at depths of between 4 and 14 m below the base of the dyke.

Due to the foundation system ‘Geotextile Encased Sand Columns’ (GEC[®]) the dyke could be constructed on the subsoil with very little shear strength and high deformability in a construction time of approx. 9 months.

Thus the foundation system ‘Geotextile-Encased Columns’ (GEC[®]) was successfully used to found the dyke in very soft soil for the purpose of land reclamation.

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