Foundation of Constructions on Very Soft Soils with Geotextile Encased Columns - State of the Art

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Abstract

Foundation systems with geotextile encased columns (GEC) are used for soil improvement and primarily for road embankment foundations in Germany, Sweden and the Netherlands since almost 10 years (*Raithel* et al, 2004), but latterly they are also used in dike construction. In this paper the essential main features of the calculation of the bearing and deformation behaviour are described. Further the know-how gained by using the different installation methods and measurement results of the foundation system ‘geotextile encased columns’ are discussed. Also a comparison of the gained settlement reduction between encased and non-encased columns (i.e. granualar piles) will be shown.

Bearing System GEC and calculation model

Bearing System GEC

With the foundation system GEC gravel-sand-columns are installed into a bearing layer to relieve the load on the soft soils. Different installation methods are thereby used. Due to the geotextile casing in combination with the surrounding soft soils the column has a radial support, whereas the casing is strained by ring tensile forces (*Raithel* et al, 2004). Due to the supporting effects of the casing, a special range of application, in opposite to conventional column foundations (i.e. granualar piles), is in very soft soils (c_u < 15 kN/m²) like peat or very soft silt/clay as well as sludge.

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. By a non-encased column, the horizontal support of the soft soil must be equal to the horizontal pressure in the column. By a GEC, 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 a stress concentration on the column head and a lower vertical pressure over the soft soil and therefore a large settlement reduction is obtained. To withstand the high ring tension forces, the geotextile casings are manufactured seamlessly. The columns act simultaneously as vertical drains, but the main effect is the load transfer to a deeper bearing layer. 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. The influence area A_E of a single column A_C in triangular grid is a hexagonal element, which can be transformed into a circular element with an equivalent area, see Figure 1.

Numerical calculation using FEM

For the numerical calculation of the GEC-System, the program PLAXIS (Finite Element Code for Soil and Rock Analyses) usually is used. An advantage of this program is the possibility to use several soil models. For soft soils, the Soft Soil Model (SSM), a model of the Cam-Clay type, is 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, is used. For details see *Raithel* (1999).

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 1.

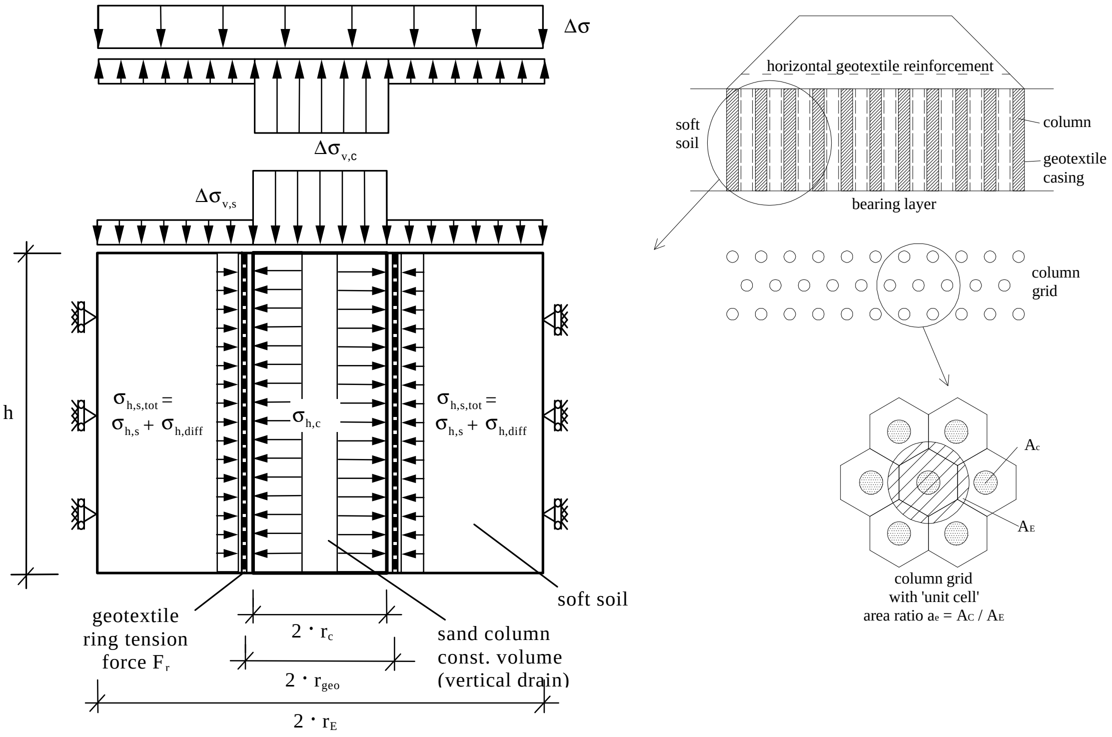

Figure 1. Calculation model ‘geotextile encased column’

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.

As shown in Figure 1, 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 surface loading $\Delta\sigma$ and the corresponding vertical stresses on the column $\Delta\sigma_{v,c}$ and the soft soil $\Delta\sigma_{v,s}$, it can be stated:

$$?s \cdot A_E = ?s_{v,c} \cdot A_c + ?s_{v,s} \cdot (A_E - A_c)$$

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 $K_{0,s}$):

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

$$\sigma_{h,s} = \Delta\sigma_{v,s} \cdot K_{0,s} + \sigma_{v,0,s} \cdot K_{0,s}*$$

The geotextile casing (radius r_{geo}) has a 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:

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

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:

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

The stress difference results in an expansion of the column. The horizontal deformation Δr_c and the settlement of the soft soil s_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 (oedometric modulus $E_{oed,s,}$ poisson ratio ν_s):

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

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

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

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

Installation method

Road and railroad engineering

Normally two installation methods are in practice. With the excavation method, an open steel pipe is driven into the bearing layer and its contents is removed by soil auger. By the vibro displacement method, 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. After that the geotextile casing is installed and filled with sand. After retrieval of the pipe under vibration a GEC filled with sand/gravel of medium density is produced. In figure 2 the vibro displacement method (left) and the excavation method (right) are shown.

Figure 2. Column installation methods

The excavation method should be preferred by soils with high penetration resistance or when vibration effects on nearby buildings and road installations have to be minimised. The advantage of the vibro displacement method compared to the excavation method is based on the faster and more economical column installation and the effects of pre-stressing the soft soil. Furthermore it is not necessary to excavate and dispose soil. Admittedly the excess pore water pressure, the vibrations and deformations have to be considered.

Hydraulic engineering from offshore pontoons

Dikes are constructed mainly with the more economical and faster vibro displacement method. By using pontoons it is possible to install columns in soils with almost no shear strength (i.e. sludge). Figure 3 shows a hydraulic engineering project using several pontoons for column installation.

Figure 3. Column installation in hydraulic engineering

Effects of installation methods

The effects and influences in the subsoil due to the column installation have to be considered. Particularly by using the vibro displacement method a contraction of the geotextile below the inner-diameter of the displacement pipe is occurring due to the stresses in the soft soils. This contraction is proved by several measurements.

The displacement of the soft soil led to an uplifting of the soft soil within and around the columns. The heaving produced wavelike deformations at the surface of the grid. The lifting was measured at up to 3-8 % of the column depth. Liquefaction of the soft soil by compaction energy was not observed. Measurements show an increase in the undrained shear strength of the soft soil surrounding the columns (figure 4). Further, an increase by a factor of 2 in the shear strength of the surrounding soft soil was measured, which shows the additional stabilizing effect of the installation method.

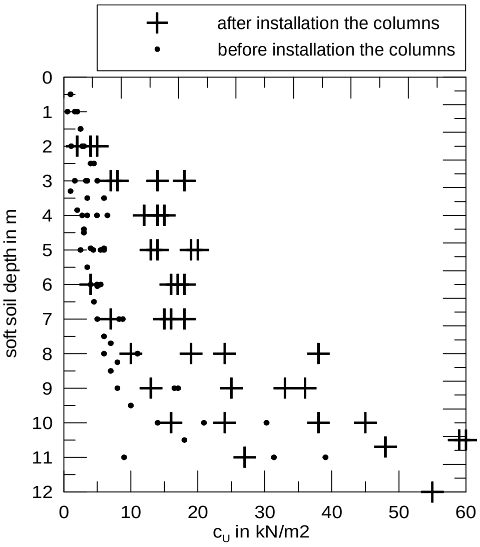

Figure 4. Increase of the undrained shear strenght in the soft soil between the columns in comparison before and after installation the columns

Project experiences

Up to the middle of the nineties first experiences installing systems with encased columns were made. But the required techniques for installing a complete, self-regulating respectively interactive bearing system and the appropriate calculation models were developed since 1994. First bearing test on encased columns took place in Germany in 1994 and in 1996 the first foundation system ‘geotextile encased columns (GEC)’ for widening an about 5 m high railroad embankment on peat and clay soils in Hamburg was carried out (*Kempfert* et al, 1997).

Meanwhile the appropriate calculation model to calculate the ring tension forces and the settlements as realistic as possible by considering the different interactions between soft soil, casing and column was developed. Up to now there are more than 15 reference projects in Germany, Sweden and the Netherlands, see table 1.

Table 1. Accomplished project with geotextile encased gravel/sand columns

year	project	construction	dam height [m]	soft soil [m]	∅ [cm]	method	A_C/A_E [%]
			road and railroad construction				
1996	Waltershof	railroad embankment	5	5	154	excavation	25 - 30
1996	Baden -Baden	railroad embankment	4	5	65	displac.	20
1998	Bruchsal	road embankment	13	5	80	displac.	20
1998	Grafing	railroad embankment	3	10	80	displac.	17
1998	Saarmund	highway embankment	5.5	10	80	displac.	10
1998	Niederlehme	highway embankment	5	7	80	displac.	14
1999	Herrnburg	railroad embankment	40	11	80	excavation	15
1999	Tessenitz-Tal	highway embankment	5	10	80	displac.	10
2000	Krempe	bridge ramp	8	7	80	displac.	13-20
2000	Grafing	railroad embankment	2-4	6.5	80	displac.	15
2000	Sinzheim	railroad embankment	2	7	80	excavation	15
2001	Hoeksche Waard	test field	2-5	10	80	displac.	5-20
2001	s’Gravendeel	test field	5	10	80	displac.	15
2001	Brandenburg	bridge ramp	7	15	80	displac.	13-18
2001	Betuweroute	bridge ramp	7	8	80	displac.	10-15
2001	Botniabahn	bridge ramp	8	8	80	displac.	15
2002	Westrik	railroad embankment	7	6 (waste)	80	displac.	15
2003	Oldenburg	railroad embankment	1.5	6	60	displac.	15
			water construction – EADS area extension				
2001 2003	polder enclosing dike	flood protection dike	9.5	14	80	displac.	10-20
2003 2004	’Finkenwerder Vordeich’	flood protection dike	9.5	12	80	displac.	15

In the following one chosen project from both road and hydraulic engineering is shown and discussed.

Road and railroad construction

As shown in table 1, especially in road and railroad construction extensive experiences with the system GEC exist. By means of measurements the effectfivness of the accomplished GEC foundations could be proved. As an example the ground improvement at the railroad Karlsruhe-Basel is shown in the following. The 1 to 2 m high embankment was founded on a approx. 7 m thick alternating sequence of peat, sludge and clay layers with stiffness between E_s = 0.7 and 2.3 MN/m². To avoid vibrations at the existing rail track the columns (∅ 80 cm) were installed using the excavation method. The situation on site and typical measurements are shown in figure 5.

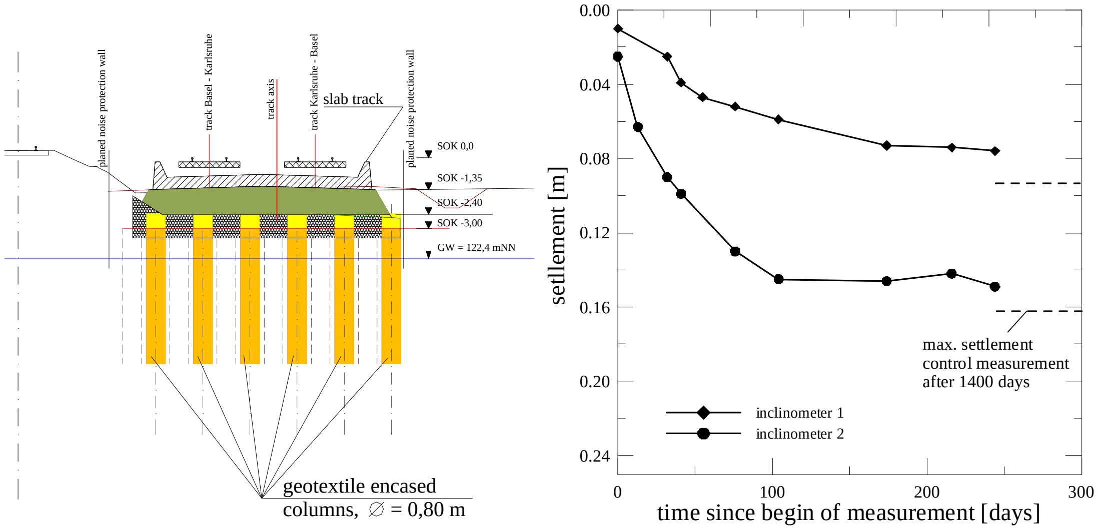

Figure 5. Foundation and typical measurements at the project ABS/NBS Karlsruhe-Basel (project Sinzheim, 2000)

Hydraulic Engineering

Beside using the foundation system in road construction there are meanwhile experiences in major hydraulic construction projects. Especially the area-extension of the airplane dockyard (EADS) in Hamburg-Finkenwerder by approx. 140 ha (346-acres) for the production of the new Airbus A 380 has to be mentioned. The area-extension is located in the ‘Mühlenberger Loch’ adjacent to the west of the existing factory site. The area extension is carried out by enclosing the polder with a 2.4 km long dike to fill up in the area under buoyancy, see figure 6.

Figure 6. Concept to reclaim land by the construction of a polder

The dike foundation was realized by about 60,000 geotextile encased columns with a diameter of 80 cm, which were sunk to the bearing layers with depth between 4 and 14 m below the base of the dike footing. This dike is the new main water protection dike of the airplane dockyard. Furthermore another 10,000 columns were installed to relocate the existing ‘Finkenwerder Vordeich’ towards the river Elbe and to avoid sludge replacement, to increase the stability and to decrease the settlements of the dike. Typical soil conditions are shown in figure 7.

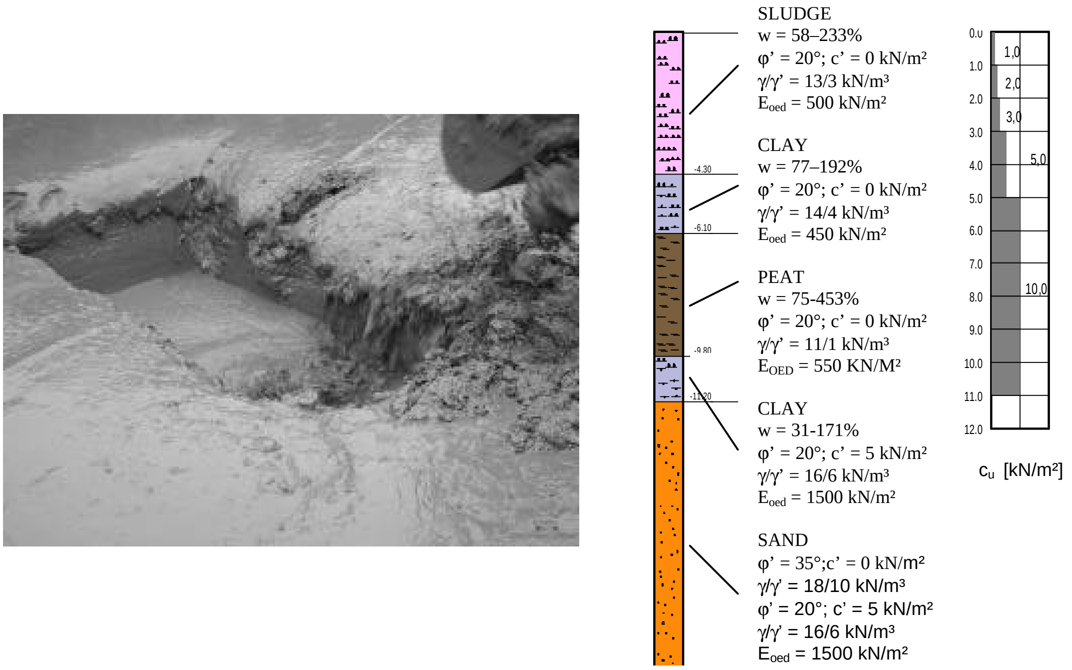

Figure 7. Typical soil boundary conditions at the area-extension of the airplane dockyard at Hamburg-Finkenwerder

Due to the foundation system GEC the dike could be constructed to a flood water save height of 7 m in a construction time of approx. 9 months. To complete the dike up to approx. 10 m, inclusive a cover of organic clay, a construction time of only approx. 15 month was necessary.

Due to the different soil conditions along the dike length 7 measurement cross sections were 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. The measured settlement in dike section VI are shown in figure 8.

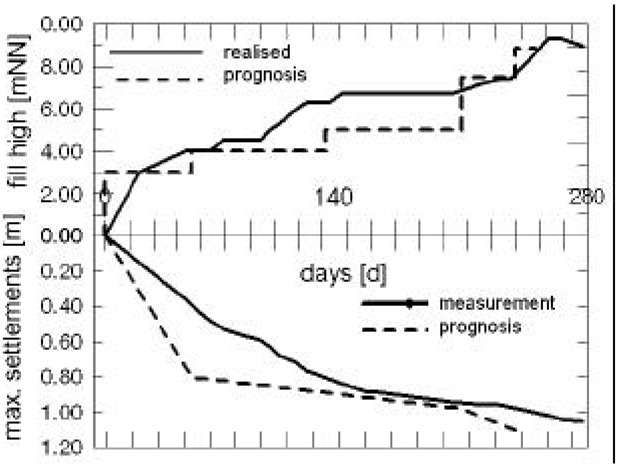

Figure 8. Measured settlements, for example in section VI

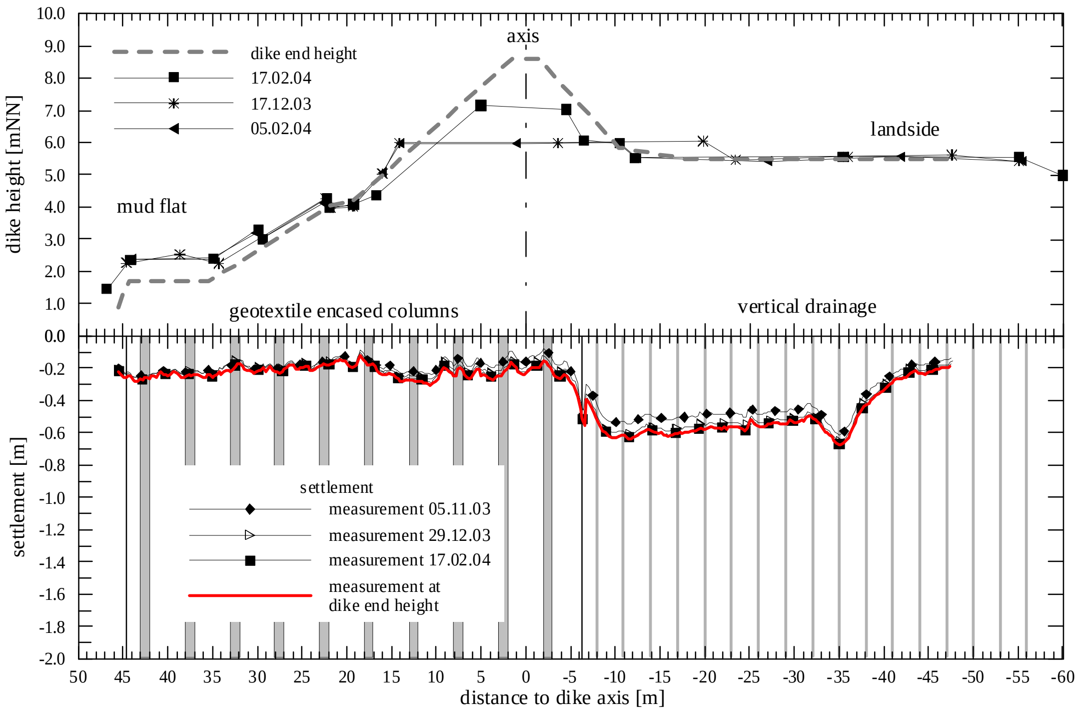

Figure 9. Measured settlements ‘Finkenwerder Vordeich’ (for example)

The dike ’Finkenwerder Vordeich Süd’ is only partly founded on encased columns. In the part outside the main load area vertical drainage is used to accelerate the settlements. Figure 9 shows typical measurement results pointing out the different settlement reduction in the part with encased columns (thickness of soft soil about 7 m) and the part with vertical drainage (thickness of soft soil about 4.5 m). The foundation system proved its value by flexibility during installation and by short time of consolidation. Therefore it was possible to build up the dike almost continuously in separate layers. For detailed specification about using the encased columns at this project see *Raithel* et al, 2004.

Summary

To assess the effectiveness (β = settlement without/with columns) of 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 foundations with granular piles (fig. 10), see also *Kempfert* (2003).

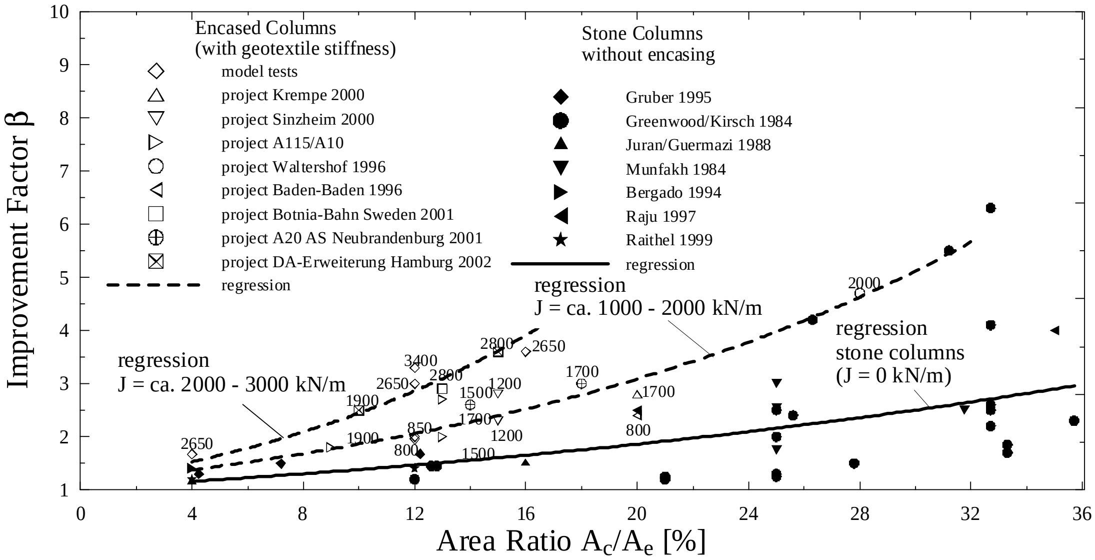

Figure 10. Soil improvement factors depending on area replacement ratio

By combining the geotextile encased columns with horizontal geotextile reinforcement (loadtransfer mat) it is meanwhile possible to construct foundations in even more difficult subsoil circumstances successfully. The effectiveness respectively the settlement reduction can be forecasted with sufficient and high reliability if adequate and aligned laboratory and field test are made.

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