CALCULATION MODELS FOR DAM FOUNDATIONS WITH GEOTEXTILE COATED SAND COLUMNS

Dr. Marc Raithel[1] and Prof. Hans-Georg Kempfert[2]

ABSTRACT

As against conventional column foundations, coated columns can be used as ground improvement in very soft soils. The radial support is guaranteed through the composite between the geotextile coating and the surrounding soil, while the geotextile is under ring tension forces. Therefore this foundation system will be employed widely to found buildings, especially embankments on very soft or organic soils like peat. Numerical and analytical models for calculation and design of the new foundation system will be reflectet.

INTRODUCTION

By the foundation of buildings on soft soils often an improvement of the soft soil with the already known column foundations was carried out for example compacted sand columns or vibro displacement granular piles. In very soft soils like peat this columns normally can not be used, because the horizontal support in this soils is not sufficient. By the new foundation method 'geotextile coated sand columns', sand columns are inserted down to the bearing layer. These columns are coated with a geotextile of polyester threads, which guarantees the filter effect and the horizontal support. By using this new developed system a safe and flexible foundation on very soft soils with low settlements, especially for dams or traffic roads embankments, can be achieved.

CONSTRUCTION PROCEDURE

Two construction methods are developed by the Josef Möbius Baugesellschaft GmbH, Hamburg, Germany, which are called the excavation method and the displacement method. By the excavation method a casing with a diameter between 0,8 m and 1,5 m is vibrated into the ground and after that the soil in the casing is excavated. Opposite to that by the displacement method a steel tube with a much smaller diameter of about 0,6 m to 0,8 m is placed into the subsoil. According to the displacement principle, the two base flaps of the casing are closed and displaces the soft soil to the sides of the casing. Then the geotextile with a somewhat larger diameter as the column is inserted into the casing. This is delivered from the factory and cut in length on the construction site. On the one hand this is due to the construction, on the other hand it ensures the partial mobilisation of the passive earth pressure, which increases the horizontal support. After inserting the geotextile and the filling of the column the casings are pulled using vibration, which causes compaction of the sand-gravel mixture in the column.

BEARING BEHAVIOUR

The geotextile coated sand columns are a bearing component, although the column must be horizontally supported. In contradiction to a conventional not coated column, where the horizontal support of the soft soil $\sigma_{h,s,tot}$ must be equal to the horizontal pressure $\sigma_{h,c}$ in the column, geotextile coated columns can be used as soil improvement in very soft soils, due to the radial supporting effect of the coating $\sigma_{h,geo} = f(F_r)$ combined with the surrounding soft soil $\sigma_{h,s,tot}$. At the same time the coating is demanded to ring tension forces F_r.

So the horizontal support of the soft soil $\sigma_{h,s,tot}$, which depends on the vertical pressure on the soft soil $\sigma_{v,s}$, can be much smaller, and a large settlement reduction is given due to the load concentration over the sand columns. Finally a load-dependent equilibrium state, with a flexible and self-regulating bearing behaviour is reached. At the same time a settlement acceleration is observed, since the columns behave as large vertical drains. After construction time, only small settlements will occur.

[1] Dr. Marc Raithel, Geotechnique Consultants Kempfert +Partner, Mannheim, Germany
[2] Prof. Hans-Georg Kempfert, Institute of Geotechnique, University of Kassel, Germany

CALCULATION METHODS

Numerical calculation using FEM

For the numerical calculation 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. The program PLAXIS allows only calculations with an axial symmetric model or a cross model. In practice a three-dimensional calculation model is hardly used. Therefore in the numerical analysis the problem is simplified and the calculation is split up into two separate models. By the examination of a single column (according to the 'unit cell concept') 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 a dam foundation, a cross model is used. The coating can not 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 parameter as well as comparative calculations are shown in Raithel (1999) and Raithel and Henne (2000).

Analytical Calculation model

Assumptions and boundary conditions

The analytical, axial symmetric calculation model (according to the 'unit cell concept') with the essential boundary conditions is shown in figure 1.

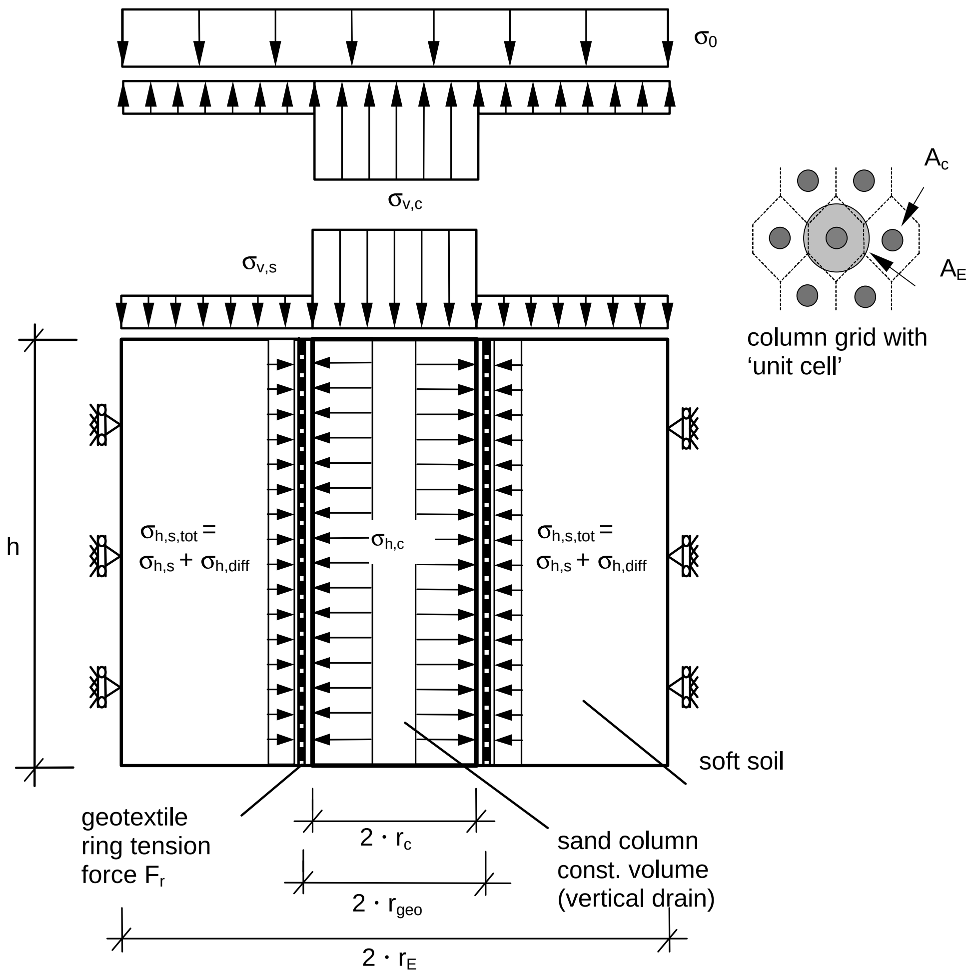


Figure 1 : Calculation model 'geotextile coated sand column'

Apart from the boundary conditions in figure 1 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 the earth pressure at rest with $K_s = K_{0,s} = 1 - \sin\phi$ is valid, if the displacement method is used an enlarged coefficient of earth pressure $K_s = K_{0,s}*$ is given before loading.
- The geotextile coating has a linear-elastic material behaviour.
- For design of the foundation the drained (end) condition is decisive, because then the maximum settlements and ring tension forces are reached.

The model was developed on the basis of the conventional calculation models used for granular piles, for example Priebe (1976), Goughnour and Bayuk (1979) and Ghionna and Jamiolkowski (1981), which are completed by the effect of the geotextile coating. For the analytical calculation of the consolidation or settlement acceleration the conventional calculation methods can be used.

Derivation

In view of the equilibrium between the loading $\Delta\sigma_0$ and the corresponding vertical stresses over the column $\Delta\sigma_{v,c}$ and the soft soil $\Delta\sigma_{v,s}$ can be written:

$$\Delta s_{0} \cdot A_E = \Delta s_{v,c} \cdot A_c + \Delta s_{v,s} \cdot (A_E - A_c) \tag{1}$$

The vertical stresses due to the loading and the different soil weights produces 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 $K_{0,s}$):

$$\Delta s_{h,c} = \Delta s_{v,c} \cdot K_{a,c} + s_{v,0,c} \cdot K_{a,c} \tag{2}$$

$$\Delta s_{h,s} = \Delta s_{v,s} \cdot K_{0,s} + s_{v,0,s} \cdot K_{0,s}* \tag{3}$$

The geotextile coating (radius r_{geo}) has a linear-elastic material behaviour with the stiffness J:

$$\Delta F_r = J \cdot \frac{\Delta r_{geo}}{r_{geo}} \tag{4}$$

The ring tension force can be transformed in a horizontal stress $\Delta\sigma_{h,geo}$:

$$\Delta s_{h,geo} = \frac{\Delta F_r}{r_{geo}} \tag{5}$$

By the use of the separate horizontal stresses a difference horizontal stress $\Delta\sigma_{h,diff}$ can be defined. This difference stress means the partial mobilisation of the passive earth pressure in the surrounding soft soil:

$$\Delta s_{h,diff} = \Delta s_{h,c} - (\Delta s_{h,s} + \Delta s_{h,geo}) \tag{6}$$

The stress difference results an expansion of the column. The horizontal deformation Δr_c and the settlement of the soft soil s_s (oedometric modulus $E_{oed,s}$) are calculated according to Ghionna and Jamiolkowski (1981) for a radial and longitudinal loaded hollow cylinder (ν_s = poisson ratio of the soft soil):

$$\Delta r_c = \frac{\Delta s_{h,diff}}{E*} \cdot \left(\frac{1}{a_E} - 1 \right) \cdot r_c \tag{7}$$

$$s_s = \left(\frac{\Delta s_{v,s}}{E_{oed,s}} - 2 \cdot \frac{1}{E*} \cdot \frac{n_s}{1-n_s} \cdot \Delta s_{h,diff} \right) \cdot h \tag{8}$$

with: $$E* = \left(\frac{1}{1-n_s} + \frac{1}{1+n_s} \cdot \frac{1}{a_E} \right) \cdot \frac{(1+n_s) \cdot (1-2n_s)}{(1-n_s)} \cdot E_{oed,s} \quad \text{and} \quad a_E = \frac{A_C}{A_E}$$

If a constant volume of the column material is assumed the following equation can be given.:

$$s_c = \left(1 - \frac{r_0^{\,2}}{(r_0 + \Delta r_c)^2} \right) \cdot h_0 \tag{9}$$

Using the above equation it must be considered, that this is only a geometric correlation. That means, if the calculation is carried out in several load increments, each time the initial high h_0 and the initial radius r_0 must be newly calculated, otherwise $r_0 = r_c$ and $h_0 = h$ can be used.

A comparability of the horizontal deformations must be given:

$$\Delta r_c = \Delta r_{geo} + (r_{geo} - r_c) \tag{10}$$

There are equal settlements between the column and the soft soil:

$$s_c = s_s \tag{11}$$

At last the following calculation equation can be derived:

$$\left\{ \frac{\Delta s_{v,s}}{E_{oed,s}} - \frac{2}{E*} \cdot \frac{n_s}{1-n_s} \left[\begin{array}{l} K_{a,c} \cdot \left(\frac{1}{a_E} \cdot \Delta s_0 - \frac{1-a_E}{a_E} \cdot \Delta s_{v,s} + s_{v,0,c} \right) - \\ K_{0,s} \cdot \Delta s_{v,s} - K_{0,s}* \cdot s_{v,0,s} + \frac{(r_{geo} - r_c) \cdot J}{r_{geo}^{\,2}} - \frac{\Delta r_c \cdot J}{r_{geo}^{\,2}} \end{array} \right] \right\} \cdot h = \left[1 - \frac{r_c^{\,2}}{(r_c + \Delta r_c)^2} \right] \cdot h \tag{12}$$

with $$\Delta r_c = \frac{K_{a,c} \cdot \left(\frac{1}{a_E} \cdot \Delta s_0 - \frac{1-a_E}{a_E} \cdot \Delta s_{v,s} + s_{v,0,c} \right) - K_{0,s} \cdot \Delta s_{v,s} - K_{0,s}* \cdot s_{v,0,s} + \frac{(r_{geo} - r_c) \cdot J}{r_{geo}^{\,2}}}{\frac{E*}{(1/a_E - 1) \cdot r_c} + \frac{J}{r_{geo}^{\,2}}} \tag{13}$$

Putting Δr_c from equation (13) into equation (12) only $\Delta\sigma_{v,s}$ is undetermined. Equation (12) can be solved by an iteration process. Due to the relatively time consuming calculation process it is advised to use a calculation program. The oedometric modulus $E_{oed,s}$ of the soft soil should be determined realistically, depending on the existing stress p*. The following equation can be used, where $E_{oed,s,ref}$ is the reference oedometric modulus for the reference stress p_{ref}. By determination of the stresses p* and p_{ref} an additional cohesion therm c·cotϕ after Schad (1979) is used.

$$\mathrm{E}_{\mathrm{oed,s}} = \mathrm{E}_{\mathrm{oed,s,ref}} \cdot (p*/p_{ref})^m \tag{14}$$

More details, such as an extension of the calculation model for several soil layers and a simplified calculation model are shown in Raithel (1999) and Raithel and Kempfert (1999).

Comperative calculation and parameter studies

By using a calculation program comparative calculations with the results of large scale model tests (scale 1:1) and numerical calculations were carried out. The used input parameters are shown in table 1, more details are documented in Raithel (1999). In addition a parameter study with defined boundary conditions was carried out. The chosen input parameters are shown in table 1. The calculation results can be seen in the figures 2, 3 and 4.

Table 1 : Input parameters for calculations

a_E [-]	h [m]	r_c [m]	r_{geo}-r_c [m]	J [kN/m]	$E_{oed,s,ref}$ [kN/m²]	c_s [kN/m²]	ϕ_s [°]	ϕ_c [°]	γ_s/γ_c [kN/m³]	$K_{0,s}$ [-]	$p_{ref}/m/\nu_s$ [kN/m²] [-]
large scale model test (scale 1:1)											
0,125	1,25	0,3375	0,0125	800	725	9	24	38	8/18	0,59	100/1/0,4
Parameter study											
Fig. 3	2,0	0,5	0,015	Fig. 4	725	5	20	37,5	3/10	0,66	100/1/0,4

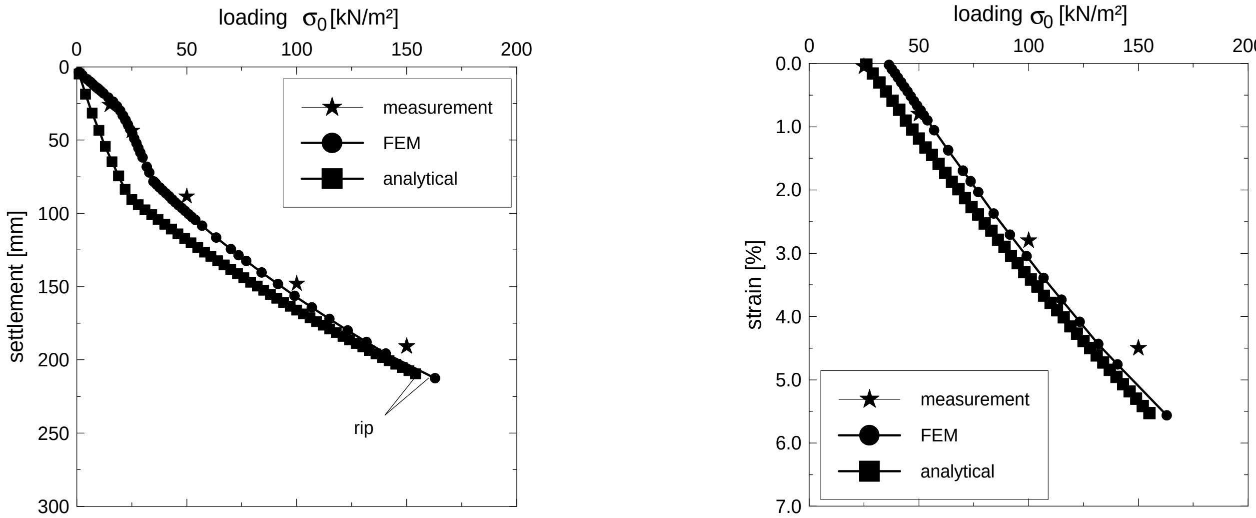


Figure 2 : Comparative calculation - large scale model test a) Load-settlement curve b) Load-strain curve

Generally a good approach can be seen. Only by small loading, before activation of ring tension forces, larger differences exist. After the activation of the ring tension forces the curves are approximate linear, due to the linear-elastic material behaviour of the geotextile coating, which is decisive for the behaviour of the foundation system. The results get closer by increase of the loading, so during serviceability state only very small differences are observed.

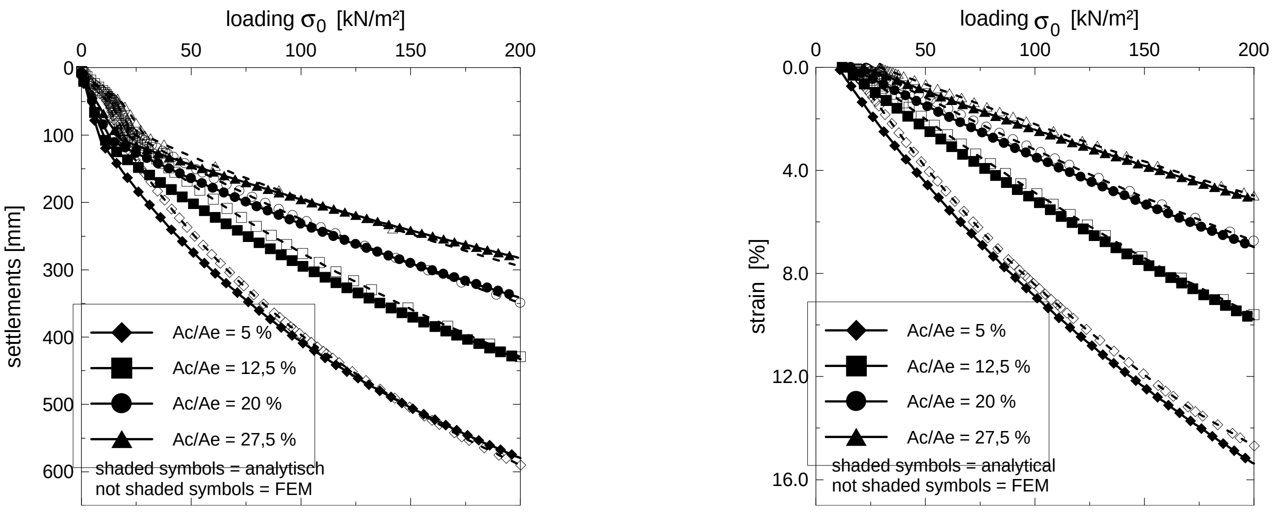
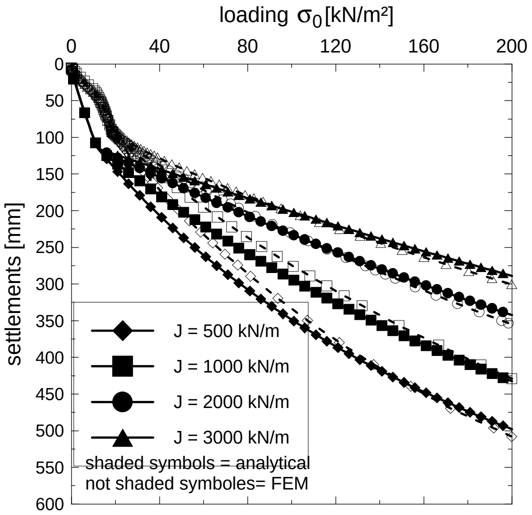


Figure 3 : Parameter study: Variation of the area ratio $a_E = A_c/A_E$ for J = 1000 kN/m



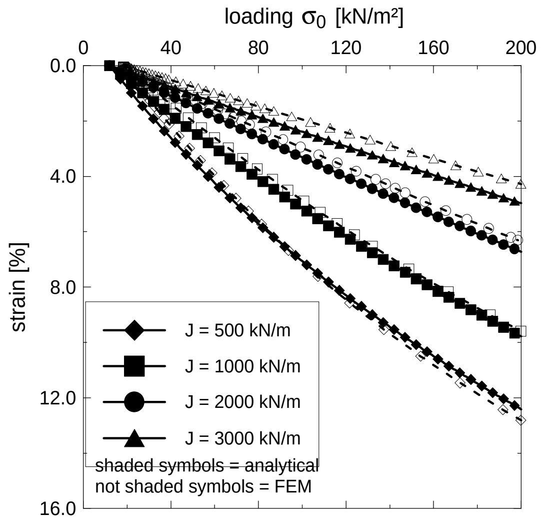


Figure 4 : Parameter study: Variation of the geotextile tensile stiffness J for a_E = 12,5 %

On the basis of the parameter studies, it can be shown, that the ring tension forces and the settlements definitely depend on the stiffness of the geotextile and the area ratio of the column grid. This is important for the design of a geotextile coated sand columns foundation, in order to calculate minimum grid distances by given soil conditions and chosen geotextile. With regard to the soil parameters, the most important parameter is the oedometric modulus.

CONCLUSIONS

In this contribution numerical and analytical models for calculation and design of the foundation system 'geotextile coated sand columns' was reflected. The most important advantage of the new foundation system is the possibility to use this system in very soft soils like peat, because the radial support is guaranteed through the composite between the coating and the surrounding soil. On soft organic soils underlain by bearing layers in reachable depths the new foundation system provides the possibility to build safe and flexible foundations with low settlements due to enormous settlement reduction, acceleration of settlements and increase of the shear strength.

REFERENCES

Ghionna, V., Jamiolkowski, M. (1981): "Colonne di ghiaia". X Ciclo di conferenze dedicate ai problemi di meccanica dei terreni e ingegneria delle fondazioni metodi di miglioramento dei terreni. Politecnico di Torino Ingegneria, atti dell'istituto di scienza delle costruzioni, n°507.

Goughnour, R. R., Bayuk, A. A. (1979). "Analysis of Stone Column-Soil Matrix Interaction under Vertical Load". C.R. Colleque int. sur le reforcement des sols: Terre armée et autres méthodes. Paris, Vol. I, pp. 271-277.

Priebe, H. (1976). "Abschätzung des Setzungsverhaltens eines durch Stopfverdichtung verbesserten Baugrundes". *Die Bautechnik,* 5, pp. 160 - 162.

Raithel, M. (1999). "Zum Trag- und Verformungsverhalten von geokunststoffummantelten Sandsäulen". Schriftenreihe Geotechnik, Universität Gesamthochschule Kassel, Heft 6.

Raithel, M., Henne J. (2000). "Design and numerical calculation of a dam foundation with geotextile coated sand columns". Proceedings of the 4th International Conference on Ground Improvement Geosystems, Helsinki.

Raithel, M., Kempfert, H.-G. (1999). "Bemessung von geokunststoffummantelten Sandsäulen". *Die Bautechnik*, 76, Heft 12.

Schad, H. (1979). "Nichtlineare Stoffgleichungen für Böden und ihre Verwendung bei der numerischen Analyse von Grundbauaufgaben". Baugrundinstitut, Universität Stuttgart, Mitteilung 10.