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GEOSYNTHETIC ENCASED COLUMNS
Behavior of a modified design model with parametric studies

Foundation of embankments on sand or stone columns and on geosynthetic encased columns (GEC) are one of the most popular methods of an improvement of a weak subsoil with a low bearing capacity and a low stiffness. This methods enable construction of structures which tolerate some settlements over weak soils by transferring the load to the stiffer underlying layer and lead to improvement of soft soil between columns due to consolidation.

Due to their higher stiffness, the columns are much more loaded then the surrounding soft soil. Existing design methods for the geotextile encased columns omit some important aspects, such as: soil improvement during installation of columns (especially by displacement method), settlement of the base of columns, etc.. This paper presents a design model for Geosynthetic Encased Columns which can be useful, especially for the design of foundations on ultra soft organic soils. Based on large parametric studies the influence of the most significant factors on the mechanical behavior of GEC model will be presented and discussed in the paper.

Introduction

GEC columns are extension of well known “traditional” sand or stone columns, which are installed in soft soils with a low bearing capacity and a low stiffness modulus. GEC system has been used successfully for soil improvement for almost 20 years, [9]. In this period many projects have been realized, some of them in very hard conditions, for example the dike on a very soft sludge in Hamburg (s_u= 0,4 - 10 kN/m^2) [3] or embankment of A2 highway in Poland on deep layer of organic soils (up to 28 m) [8].

Extension of the traditional mineral column technology is based on geotextile encasement around the column. It protects against internal damage such as: an excessive lateral deformation (bulging) and also prevents from squeezing out of the mineral filling. A mechanical behavior of geotextile encased columns has been investigated in many laboratories and numerical studies in recent years, [5,6]. Generally conclusions are that the encasement leads to decreasing settlements and increasing bearing capacity of mineral columns. In opposite to ordinary stone columns GEC system can be used in very soft soils with a very low lateral support [3,8,9].

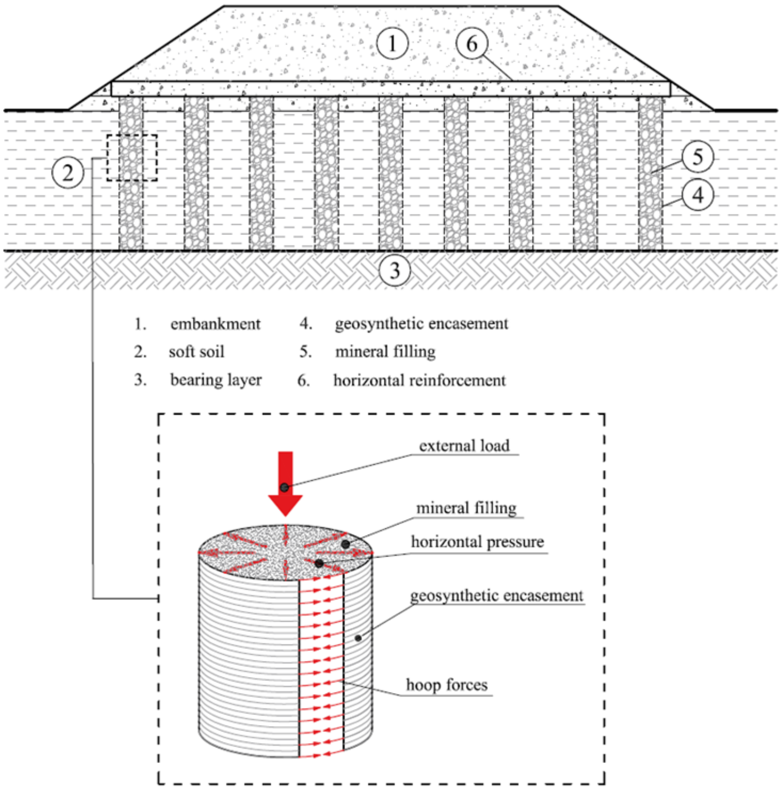


Figure 1 Scheme of GEC system (HUESKER)

Among calculation methods of GEC columns the most popular and accepted one was presented by Raithel [1]. This method is based on an unit cell concept, where columns and the surrounding soft soil are treated as an axial symmetric cell system. This procedure of the design is widely shown in German Recommendations EBGEO [4]. In recent years some different models were published [5,7,11]. This paper focuses on Meyer – Łopatka model [11] in which the most important features are:

- nonlinear dependency between load and settlement of soft soil (stiffness of soft soil is a function of porosity);
- bearing ground under column is compressible;
- method of installation of columns affects stiffness of soft soil.

This paper shows behaviour of GEC model by showing the influence of the most significant factors on the effectiveness of the supporting system and safety of the individual column.

description of model

Meyer - Łopatka model is described in details in [11], in this part only the most important assumptions and dependencies are shown.

Diameter of unit cell D_e depends on geometry of column grid and it is a result of converting influence area A_0 to equivalent area of circle. Geometric relations between typical column grids and unit cell are shown in Figure 2.

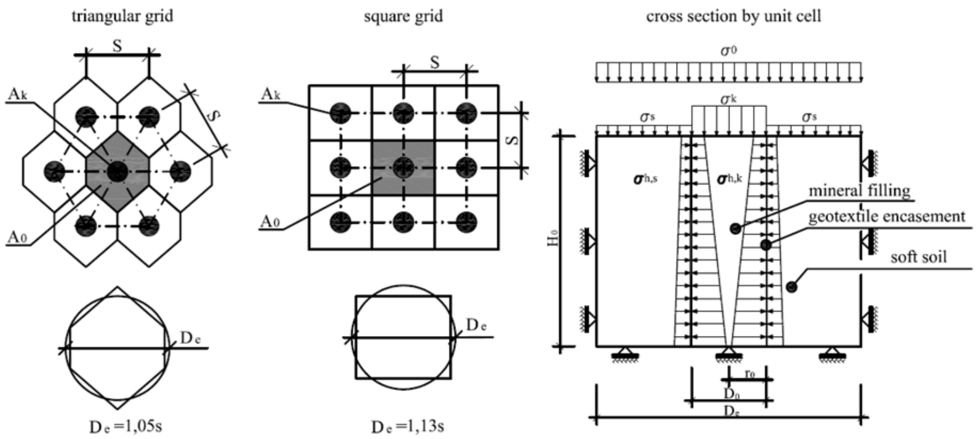


Figure 2 Typical column grids and unit cells incl. a cross-section of the unit cell

where:

- S – axial spacing between columns, [m]
- A_k – cross-section area of column, [m^2]
- A_0 – cross-section area of unit cell, [m^2]
- D_0 – diameter of column, [m]
- D_e – diameter of unit cell, [m]
- H_0 – thickness of soft layer (length of the column), [m]
- σ_0 – vertical stress on the unit cell top surface, [kN/m^2]
- σ_s – vertical stress on the top of soft soil, [kN/m^2]
- σ_k – vertical stress on column head, [kN/m^2]

An area ratio is proportion between area of column and area of unit cell. It presents displacement (or replacement) ratio of soft soil:

$$\alpha = \frac{A_k}{A_0} \tag{1}$$

In the model settlement of column head consist of two components (figure 3):

- settlement of bearing layer under column s_{kp}
- vertical deformation of column caused by horizontal deformation (bulging) s_{kr}

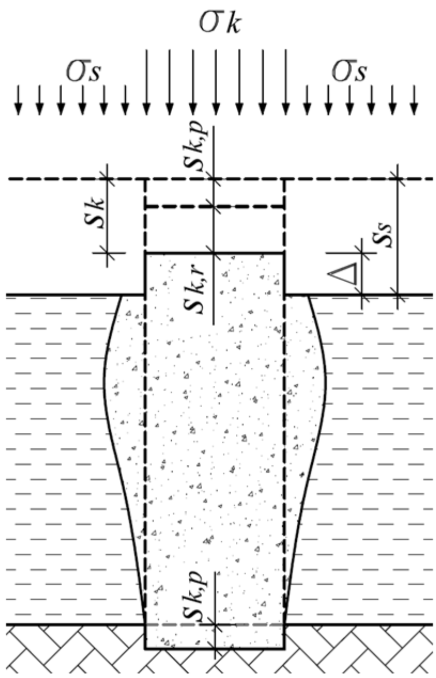


Figure 3 Settlements of GEC column

where:

s_s – settlement of soft soil (in the space between columns)
Δ - difference between settlement of soft soil and settlement of column head (in presented model Δ is an input parameter)

Settlements in bearing layer under the columns base are calculated with an assumption that there is no friction between column and surrounding soil, so the vertical stress in the bottom of column equals σ_k.

Effectiveness of the supporting (degree of unloading of soft layer) is described by a load redistribution factor E. This factor expresses part of total load which is transmitted by columns.

$$E = \frac{\sigma_k A_k}{\sigma_0 A_0} = \frac{N_k}{N_0} \tag{2}$$

where:

N_k – load of column [kN]
N_0 – total load of unit cell [kN]

The load redistribution factor is the key element during calculation. Knowing E-value it is possible to predict all system parameters such us:

- vertical stress on soft soil: σ_s [kN/m^2];
- vertical stress on column: σ_k [kN/m^2];
- settlements: s_s and s_k [m];
- tensile force in encasement: $F_{ob,i}$ [kN/m];
- strain of encasement: $\varepsilon_{ob,I}$ [%];

Counting of E parameter requires iterative calculations. We get proper value when equation (3) is solved

$$s_{k,r} + s_{k,p} = s_s - \Delta \tag{3}$$

Taking into account all expressions for settlements of column (left part of equation 3) and for the settlement of soft soil between columns, the solution takes form:

(4)

$$\sum_{i=1}^{n} H_{0,i} \frac{r_0\sigma_{h,i}\left(2J + r_0\sigma_{h,i}\right)}{\left(J + r_0\sigma_{h,i}\right)^2} + \frac{\sigma_0 E}{\alpha E_p} \frac{D_0 z_0}{D_0 + z_0} = n'_0 H_0 \left[1 - \left(1 + \frac{\kappa - 1}{n'_0} \frac{\sigma_0(1-E)}{M'_0(1-a)}\right)^{\frac{-1}{\kappa-1}}\right] - \Delta$$

where Ev(0,1), and:

$H_{0,i}$ thickness of slice i in the unit cell, [m]
n - number of slices
$\sigma_{h,i}$ - horizontal stress inside column in „i" slice [kN/m^2], s. eq. 5
J- axial tensile stiffness of encasement [kN/m]
z_0 - depth of active zone in bearing layer [m], s. eq. 6
n'_0 - porosity of soft soil after column installation [-]
M'_0- oedometric modulus of soil after column installation [kN/m²]
κ - power, for peat 1,5-2,0 (parameter is determined from oedometer test)

horizontal stress $\sigma_{h,I}$:

$$\sigma_{h,i} = \left(\frac{\sigma_0 E}{a} + \gamma'_k z_i\right)\frac{\nu_k}{1-\nu_k} - \left(\frac{\sigma_0(1-E)}{1-a} + \gamma'_s z_i\right)\frac{\nu_s}{1-\nu_s} \qquad (5)$$

where:

γ'_k - effective unit weight of mineral filling of column [kN/m^3]
γ'_s - effective unit weight of soft soil [kN/m^3]
ν_k - Poisson's ratio of mineral filling of column [-]
ν_s - Poisson's ratio of soft soil [-].

According to [10], the depth of the active zone in bearing layer could be estimated using eqn. (6):

$$z_0 = \frac{1}{2 \cdot tg\phi'} \cdot \frac{1}{\ln\left(\frac{E_p}{\sigma_k}\right)} \cdot \frac{\sigma_k}{\gamma'} \qquad (6)$$

where:

Φ' – effective angle of internal friction of soil in bearing layer [°]
γ' – effective unit weight of soil in bearing layer [kN/m^3]
E_p - Young's modulus of soil in bearing layer [kN/m²]

Knowing the value of horizontal stress in the i slice the value of elongation and tensile force can be obtained using eqn. 7 and 8:

$$F_{ob,i} = r_0 \cdot \sigma_{h,i} \qquad (7)$$

strain of encasement:

$$\varepsilon_{ob.i} = \frac{F_{ob,i}}{J} \qquad (8)$$

GEC columns can be installed by a displacement or by a replacement method. First of them may be reason for decreasing porosity of soft soil. It is possible to express change of porosity with a factor ω in range ω**v**<0,1> where:

ω=0 - there is no change in porosity (e.g. replacemant method),

ω=1 - when porosity is reduced by the α value (e.g. displacement method with assumption that the volume of soft soil in the unit cell is constant).

Porosity after installation of columns (but before loading) takes form:

$$n'_0 = n_0 - \alpha\omega \tag{9}$$

The value of the corresponding edometric modulus of soft soil after column installation (but before loading) could be estimated with eqn. 10:

$$M'_0 = M_0\left[1 + \left[\left(1 - \frac{\alpha}{n_0}\right)^{-\kappa} - 1\right]\omega\right] \tag{10}$$

where:

M_0- primary oedometric modulus of soft soil (before column installation) [kN/m²]

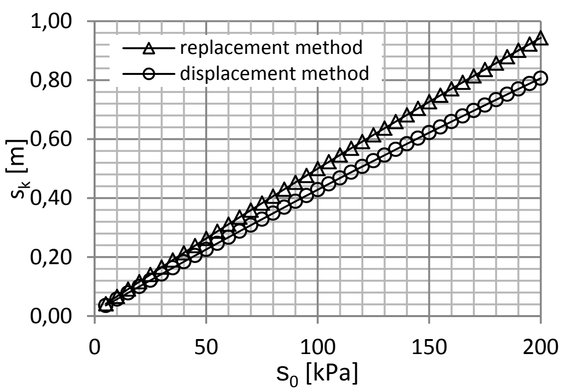
The influence of installation method

Firstly the influence of column installation method on the behavior of GEC system is shown in the Figure 4. The achieved relationships are from the data given in Table 1.

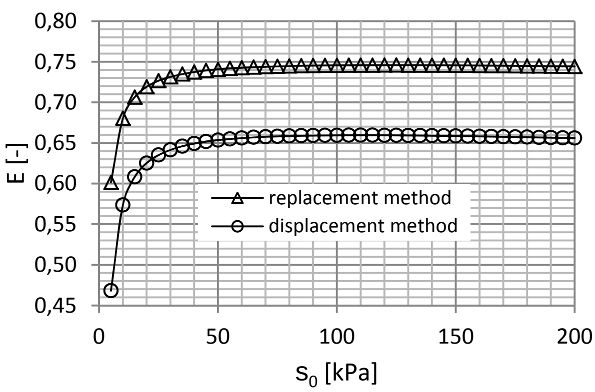
Table 1

general						soft soil					columns			bearing layer		
α [-]	D_0 [m]	H_0 [m]	n [-]	H_i [m]	Δ [m]	γ'_s [kN/m³]	n_0 [-]	M_0 [kPa]	κ [-]	ν_s [-]	γ'_k [kN/m³]	ν_k [-]	J [kN/m]	Φ' [°]	γ' [kN/m³]	E_p [MPa]
0,15	0,8	10	50	0,2	0	11	0,66	560	1,7	0,26	19	0,21	2000	31	18	40

In the current investigations the value of external vertical stress σ_0 was assumed to be in the range of 0 and 200 kN/m². The calculations were performed for both installation methods (ω=1 – displacement method, ω =0 – replacement method). Results are shown in Figure 4.



a)



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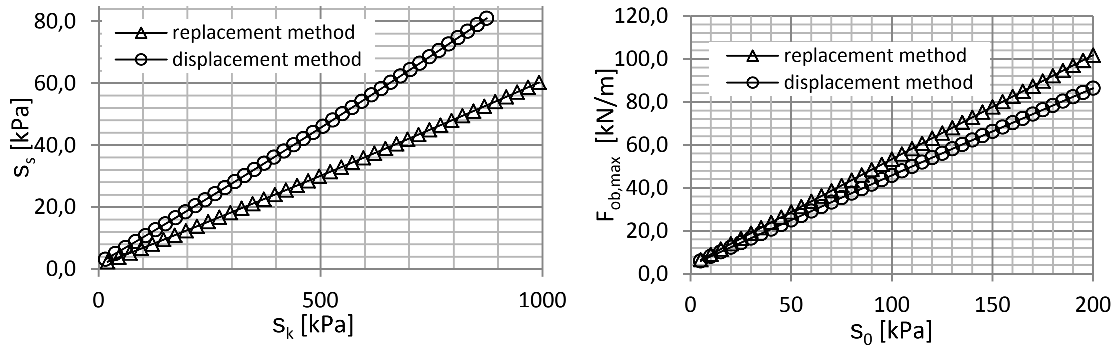


c) d)

Figure 4. The influence of installation methods on mechanical behavior of GEC

Figure 4 shows, that the installation method has a significant meaning for the mechanical behavior of GEC system. The reduction of soft soils porosity in the displacement method leads to decrease of settlements after loading (Figure 4a). In E-σ_0 dependency (Figure 4b) the load redistribution factor for displacement method is visibly lower than for the replacement method. It means, that stiffer soil between columns can sustain a higher load, what is directly shown in Figure 4c. The same value of σ_0 in the replacement method leads to a higher loading of columns and to increase of tensile forces in the encasement (Figure 4d), due to the lack of the reduction of soft soil porosity during installation of columns.

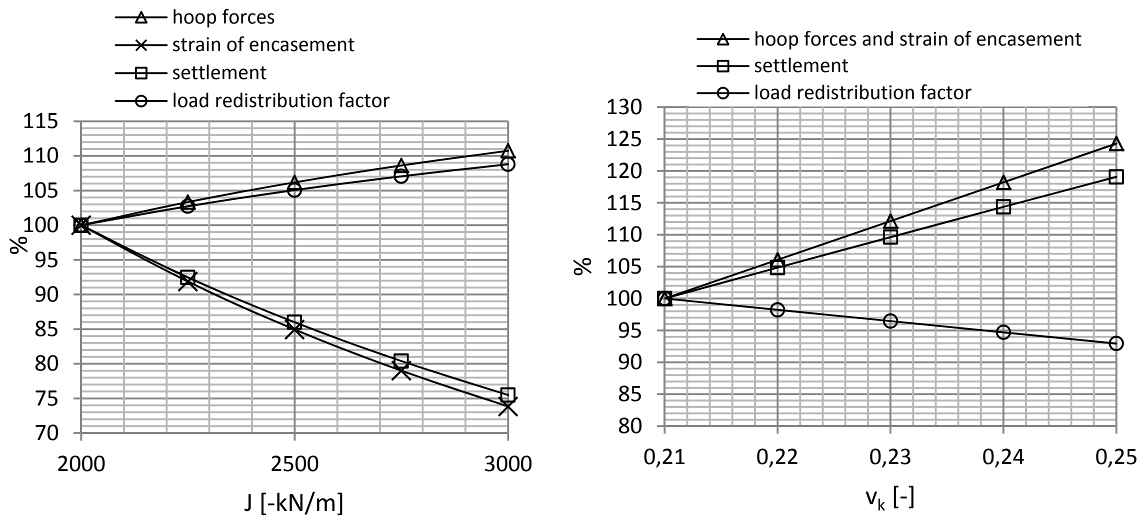
Influence of column parameters on GEC system

To check the influence of column material on mechanical behavior of GEC system in first order "a base model” was tested with input data presented in the Table 1. Here the replacement method of column installation was assumed (ω=0*)* and the value of the external vertical stress from loading equals σ_0=100 kPa. The achieved results for "base model” are shown in the Table 2.

Table 2. Results for„base model”

$F_{ob,i,max}$ [kN/m]	ε_{max} [m]	s_k=s_s [m]	E [-]
53,34	2,67	0,50	0,75

In second order few calculations were made with different values of encasement stiffness and Poisson's ratio of mineral filling. Results were compared with values of the "base model”, in which the results of “base model” ware set as 100%. The influence of those parameters on the mechanical behavior of GEC is shown on Figure 5.



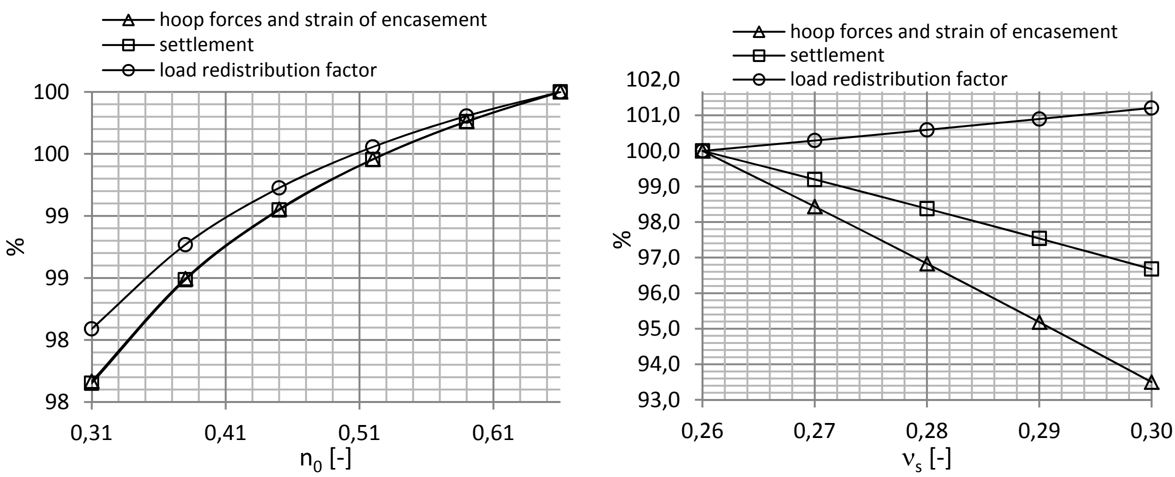
a) b)

Figure 5. Influence of column parameter on mechanical behavior of GEC

Figure 5a shows that the increase of the encasement stiffness leads to reduction of column settlements (i.e. the axial stiffness of columns increases with the increase of tensile stiffness of encasement). With higher tensile stiffness of encasement columns will be loaded higher as demonstrated by higher E-values. An increase of the Poisson's ratio-value of mineral filling (Figure 5b) leads to the increase of settlements and tensile forces of encasement. It is the effect of increasing of horizontal stresses inside columns, $\sigma_{h,i}$ and a higher vertical deformation of columns caused by expansion of the diameter.

Influence of soft soil parameters on GEC system

Only the influence of porosity n_0 and Poisson's ratio ν_s of soft soil were investigated in this study, (figure 6). The influence of oedometric modulus M_0 was omitted, because this dependence was indirectly shown in the Figure 4 which showed influence of installation method.



a) b)

Figure 6. Influence of soft soil parameters on mechanical behavior on GEC system

With a decrease of primary porosity (Figure 6a) all important system parameters also decrease. This behaviour is easy to predict, because in chosen settlement model porosity is connected with stiffness of soil. Stiffer soil surrounding columns can sustain higher horizontal and vertical stresses, which leads to the unloading effect of columns. Figure 6b shows that with an increase of Poisson's ratio of soft soil a reduction of tensile forces in encasement and settlement of columns could be registered. It is caused by lower horizontal stresses $\sigma_{h,i}$ in columns.

Conclusions

- Performed analysis shown that the most important meaning on for GEC system has stiffness of encasement and oedometric modulus of soft soil. These parameters have strong effect on load distribution and on the safety of the column.
- Presented model involves influence of installation methods on mechanical behavior of GEC system. The reduction of soil porosity caused by displacement method has a notable influence on bearing capacity and leads to reduction of settlements.
- The major component of column settlement is vertical deformation caused by horizontal displacement, (in the presented "base model" it was 98% of total value). The key to the more accurate prediction of settlement (and column safety) is better prediction of lateral stresses in mineral filling and its volatility on column length during loading.

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