Critical Height of Embankments supported by Geotextile Encased Granular Columns

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ABSTRACT

In very soft ground, the use of granular columns may be restricted due to lack of lateral confinement. In these conditions, columns may be encased by a suitable geosynthetic in order to provide the required confining pressure, increasing their bearing capacity. Avoiding differential settlements at the top of embankments is usually important to ensure levels of proper use and prevent serviceability problems in the built infrastructures. Thus, the critical height is defined as the height above which, differential settlements at the base of the embankment, do not produce measurable differential settlements at the embankment surface. This work describes two-dimensional finite element analyses carried out to study the critical height of an embankment supported by a single geotextile encased granular column (GEC) in a very soft soil, using PLAXIS 2D software. Comprehensive numerical analyses were performed, by increasing the height of the embankment, to study the influence of the tensile stiffness of the encasement, the compressibility and thickness of the soft clay layer and the span between columns, in order to access the embankment critical height.

It was concluded that the diameter and the spacing between columns are the only parameters affecting the development of the critical height. Based on the numerical results obtained, a design equation was proposed, to estimate the embankment critical height, function of the mesh configuration, column diameter and spacing between columns. It was also possible to compare the equation developed, with the available critical height results for piled embankments, concluding that there are no significant discrepancies between the two.

.**Key-words**: Soft soils, embankments, geotextile encased granular columns, critical height, finite elements

1. INTRODUCTION

Embankments built on very soft soils may experience problems such as excessive settlements, large lateral deformations of the soft soil layer beneath the embankment, and global or local instability. Ground improvement, with emphasis on the encased granular columns technique, overcomes the mentioned problems by reducing the total settlement under loading, and, additionally, by speeding up the consolidation process of the original soil. The presence of the granular columns, due their axial stiffness and bearing capacity, creates a composite material, stiffer than the original soft soil.

Conventional granular columns attain their load capacity from the confinement offered by the surrounding soil, through mobilization of the passive earth pressure. However, when granular columns are installed in very soft clay, insufficient lateral confinement, reduces their load capacity. Note that, a very soft clay is a very compressible soil associated to very small values for the undrained shear strength (C_u<15 kN/m^2). Accordingly, in these cases, the inefficient confinement offered by the soft soil can be solved involving the column with a high – modulus geosynthetic encasement, generally, a geotextile. Therefore, the main function of the used geotextile is the radial confining reinforcement of the bearing column. On the other hand, the encasement, due to its drainage, separation and filtration features, allows the columns to perform as high-capacity vertical drains, speeding up the consolidation process in the original soft soil. In addition, encasement also prevents the lateral squeezing of granular material into the surrounding soil, and vice versa.

Embankments supported by columns in general, i.e., piles, jet grouting columns or granular columns, installed in a very soft stratum, experience differential settlements at their bases, which affect the corresponding surfaces. Avoiding differential settlements at the surface of an embankment is often important to prevent distress to overlying structures and to provide adequate levels of ride quality. Therefore, the term “critical height” is defined here, as the embankment height above which differential settlements, at its base, do not produce measurable differential settlement at the embankment surface. Note that, other authors, quoted by Filz *et al*. (2012), use the definition of critical height in other ways, for example, for column elements, Horgan & Sarsby (2002) and Chen *et al*. (2008) use the definition of critical height to refer to the height above which, all additional loads, due to fill and surcharge, are distributed completely to the pile caps.

Based on bench-scale tests (McGuire, 2011) and field-scale tests (Sloan, 2011), and case history data, it was found that the factors affecting the critical height of embankments supported by piles, are mainly the columns diameter and spacing between them. From the results obtained with the tests performed by McGuire (2011), using piles in a square array, a design equation was formulated, which allows to estimate the embankment critical height, function of the columns diameter and spacing between them. Accordingly, this work refers to a two-dimensional numerical study, through the finite element method, using PLAXIS 2D software, of the parameters affecting the critical height of an embankment supported by deformable sand columns, encased by a suitable geotextile. In addition, this work ends with a comparison between the numerical results obtained here, with the results achieved by McGuire (2011) and Sloan (2011) for piled embankments, as far as the critical height is concerned.

2. GENERAL CONCEPT AND DESIGN METHODS

The general concept remains the same as for conventional piled embankments, which means to take the load from the embankment and, then, transfer it, mainly through the columns, down to a firm stratum. However, the axial compression stiffness of the piles is so high, that practically no settlement occurs at their tops. Thus, geosynthetic reinforcement is often used to help transfer the embankment loads to the piles. This high strength horizontal geosynthetic, usually a geogrid element, is typically installed above the piles to bridge over the soil between columns and equalize the embankment deformations. Conversely to piles, the vertical compressive behavior of GEC’s is less rigid. The compacted granular column starts to deform under load, mainly due to radial deformation, resulting in settlements at its top. Column deformation is mostly controlled by extension and consequent mobilization of tensile strains in the geotextile encasement. However, the mobilized ring-forces actually require some radial extension of the encasement leading to some radial “spreading” deformation in granular column, resulting in vertical settlements of its top. Thereby, the geotextile encased column system cannot be settlement free. Finally, ensured by the strength and stiffness of the granular material combined with the confining ring forces in the encasement and some confinement provided by the soft soil, a state of equilibrium is reached.

The bearing behavior and efficiency of a geotextile encased column system is complex and depends on its deformation and confinement provided to the surrounding soft soil. The bearing GEC elements are much stiffer than the adjacent soil and, consequently, attract a higher load concentration from the embankment. Conversely, the pressure acting on the surrounding soil is lowered resulting in a reduction of the total settlements. Thus, it may be conclude, that the loads from the embankment are transferred to the columns as well as to the soft soil, through the arch effect mechanism. Raithel & Kempfert (2000) presented an analytical solution for designing a geotextile encased granular columns foundation. The presented solution allows estimating the stresses and deformations, in both GEC and soft soil (Almeida *et al*., 2013). The design procedure is based on the unit cell concept shown in Figure 1.

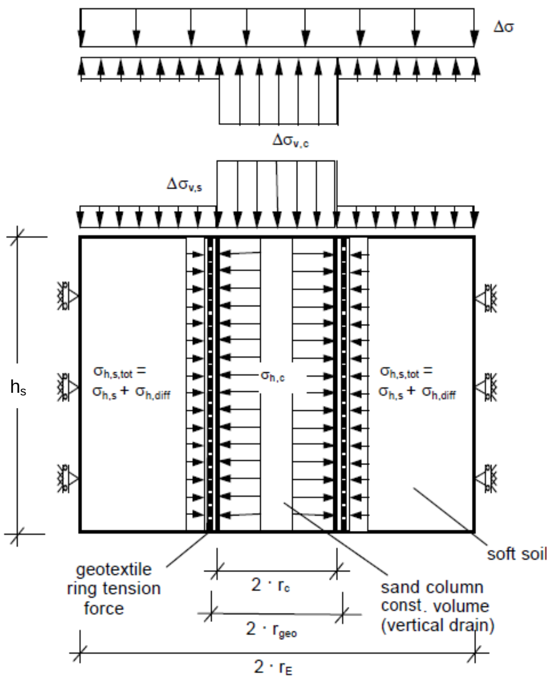

Figure 1 – Calculation model “geotextile encased column” (Alexiew *et al*., 2012)

Based on this concept, to the long-term drained condition, the average vertical stress from the embankment, $\Delta\sigma$, acts over the area of influence of a single column unit area. This column influence area is a function of the mesh configuration (rectangular or triangular) and can be turned into a circular equivalent area, A_E, defined by a diameter, d_E. The influence area of a column in a triangular array and the corresponding area of the unit cell, as well as the column area, A_c, are all represented in Figure 2.

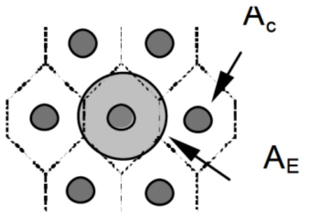

Figure 2 – Column triangular grid with unit cell (Alexiew *et al*., 2012)

The average vertical stress, $\Delta\sigma$, is proportional to the higher stress imposed on the column acting over the area of the column, A_c. The difference in vertical stresses acting over the columns, $\Delta\sigma_{v,c}$, due to concentration, and in the surrounding soil, $\Delta\sigma_{v,s}$, creates a corresponding difference in the horizontal radial stress in the column, $\sigma_{h,c}$, and in the adjacent soil, $\sigma_{h,s}$, resulting, therefore, in a ring tensile force in the encasement. Note that, knowing the radius, r_{geo}, and the change in displacement, Δr_{geo}, of the geotextile casing, and its tensile stiffness, J, the horizontal stress $\sigma_{h,geo}$ acting on the encasement is determined by Eq. [1].

$$\sigma_{h,geo} = \frac{N}{r_{geo}} \quad [1]$$

Where the ring tensile force, N, is given by Eq. [2].

$$N = J\frac{\Delta r_{geo}}{r_{geo}} \quad [2]$$

Thus, a differential horizontal stress can be defined, which represents the mobilization of the passive earth pressure in the surrounding soft soil, given by Eq. [3].

$$\sigma_{h,diff} = \sigma_{h,c} - \left(\sigma_{h,s} + \sigma_{h,geo}\right) \quad [3]$$

The differential horizontal stress results in an expansion of the column. More details of the method can be found in the paper of Alexiew *et al.* (2012).

Due to this complex interactive behavior, calculation procedures must be iterative in order to attain the final equilibrium in the system. It is recommended to support this process by appropriated software.

An extremely important concept associated to embankments supported by granular columns in general, is the area ratio, a_c, defined as the ratio between the area of the columns installed in a given soft soil area, and the area of the correspondent unit cell. Therefore, the area ratio is given by Eq. [4].

$$a_c = \frac{A_c}{A_E} \quad [4]$$

3. NUMERICAL MODELING

In order to simulate the unit cell, an axisymmetric model was undertaken through the finite element method, using PLAXID 2D software, and triangular finite elements with 15 nodal points were employed for the soil elements. Therefore, each geosynthetic element was automatically defined by five-node line elements, which act as a membrane.

The PLAXIS 2D program was used, in order to investigate the parameters affecting the critical height. Thus, the numerical analyses were carried out for several parametric studies, performed with increasing height of the embankment final layer

3.1. Material properties and geometry

Concerning the constitutive models, the soft clay was simulated using the Soft Soil model. The column material, simulated as a sand, was modeled using the Hardening Soil model, so that the oedometer modulus, E_{oed}, is stress dependent. An elasto-plastic Mohr–Coulomb model was adopted for the embankment material. And finally, the encasement and the geosynthetic reinforcement were both modeled by geogrid elements. Therefore, the geosynthetics were simulated as linear elastic materials with tensile stiffness, J, for the encasement and, J_R, for the reinforcement. Table 1 shows the data and values used in the finite element method.

To investigate the parameters affecting the embankment critical height, some of the associated data values had to be changed, such as the tensile stiffness of the encasement or the thickness of the soft clay layer. In this point, to clarify the options made in the numerical analysis, those variations were not yet taken into consideration. Thereby, the hypothetical base problem modeled, is shown, schematically for a 1,75 m embankment height, in Figure 3, which consists of a 2,4 m diameter unit cell with columns of 0,8 m diameter and 10 m length, including the encasement with a geotextile material and a single reinforcement layer at the base of the embankment using a geosynthetic material.

Table 1 – Constitutive models and properties adopted in PLAXIS 2D

Properties	Sand column (*Hardening Soil*)	Embankment (*Mohr-Coloumb*)	Soft clay (*Soft Soil*)	Encasement (*Geogrid*)	Reinforcement (*Geogrid*)
γ (kN/m^3)	20	18	14	-	-
k_x (m/dia)	1	2	1,8 x 10^{-4}	-	-
k_y (m/dia)	1	2	2,0 x 10^{-5}	-	-
E (kPa)	-	15000	-	-	-
E_{50}^{ref} (kPa)	12000	-	-	-	-
E_{oed}^{ref} (kPa)	16210	-	-	-	-
E_{ur}^{ref}(kPa)	27690				
Power (m) (-)	0,5	-	-	-	-
ν (-)	-	0,3	-	-	-
λ^* (-)	-	-	0,240	-	-
κ^* (-)	-	-	0,042	-	-
c (kPa)	0,1	1,0	5,0	-	-
ϕ (°)	40	30	28	-	-
Ψ (°)	10	0	0	-	-
EA (kN/m)	-	-	-	1000	400

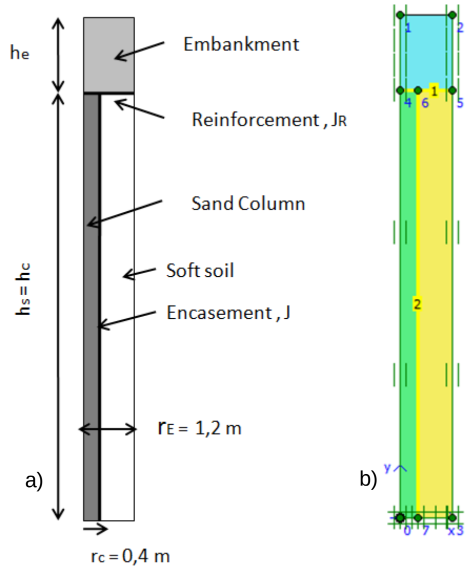

Figure 3 – Finite-element axisymmetric simulation of geotextile - encased column in unit cell concept: (a) scheme adopted in numerical analyses; (b) boundary condition and finite-element model

3.2. Model description

In the numerical model adopted, shown above in Figure 3, an axisymmetric model was undertaken, because the axis of symmetry is coincident with the axial center line of the unit cell. Figure 3 b), represents the models developed in PLAXIS 2D and shows the boundary conditions and also the materials involved, i.e., sand column, soft clay, embankment material and geotextile encasement and geosynthetic reinforcement. From this figure, it may be concluded that, the horizontal displacements were restrained in the axis of the column, and also in the external part of the unit cell. In addition, it was also assumed that the column base rests on a rigid stratum. Therefore, horizontal and vertical fixities were employed at the bottom of the column and the soft soil.

To run the program it was necessary to generate the finite element mesh and define the size of the triangular elements. In this work, a medium global coarseness mesh, refined through the geosynthetics materials, was employed.

Simulation of the installation of the encased column, which is usually by lateral displacement in very soft soils, was not modeled and the groundwater table level was considered coincident with the original soft soil surface.

Finally, finite element analysis was performed for long-term conditions (drained analysis) to assess the influence of embankment loading on the settlement, which means that, a plastic calculation was performed. Note that, with the plastic calculation, it is possible to assess the maximum values for both stress and deformations in the system. Therefore, in the numerical analyses, the embankment loading was simulated by actual embankment material placed (instantaneously) at the top of the soil/column surface.

4. PARAMETERS AFFECTING THE CRITICAL HEIGHT

To understand which parameters related to the encased sand columns in a very soft soil, affect the development of the critical height, the numerical analyses were carried out in order to support a parametric study. These parametric studies were performed with increasing height of the embankment final layer, and, also, by changing the values of some selected parameters. The chosen parameters to study were the tensile stiffness of the encasement, J, the compressibility of the soft clay layers, λ^*, the thickness of the soft clay, h_s, and, finally, the area ratio a_c. In this way, from the studies performed for each parameter, the differential settlements at the top of the embankment were investigate until the embankment critical height above which, differential movements at the base of the embankment did not produce any measurable differential movements of the embankment surface, was reached. Accordingly, the base parameters used in the calculations performed, are exposed in Table 2.

Table 2 – Base values adopted in the numerical analyses (parametric studies)

h_s (h_c)	d_c	d_E	J	J_R	λ^*	κ^*
10 m	0,8 m	2,4 m	1000 kN/m	400 kN/m	0,240	0,042

Note that, h_c is the length of the column considered equal to the soft clay thickness.

For each parameter studied, the corresponding value, presented in Table 2, was changed, while the rest of the parameters adopted, remain constant, and equal to the ones shown in that same table. Thus, for the tensile stiffness of the encasement, 3 values were considered: J = 1000, 2000 and 4000 kN/m. For the soft clay layer, modeled as a Soft Soil which is a Cam-Clay model type, its compressibility is defined by the modified compression index, λ^*, and the modified swelling index, κ^*. Consequently, for the compressibility of the soft clay, 3 values were studied: λ^* = 0,12, 0,24, 0,48 respectively associated to the follow values: κ^* = 0,021, 0,042, 0,084. Still associated to the soft clay layer, for its thickness, 3 values were simulated: h_s = 5, 10, and 15 m. Again, note that, the thickness of the soft clay layer directly affects the column length and, consequently, the length of the column is considered equal to the thickness of the clay layer. Finally, for the area ratio, 3 values were studied: a_c = 5,0%, 11,1% and 16,0%.

The area ratio depends on column diameter and also on unit cell diameter. This means the area ratio is affected by the layout of the columns (rectangular or triangular), the diameter of the rigid elements (columns) and the spcacing between columns. In a first approach to the problem, the influence of the area ratio in the development of the critical height was considered, increasing the span between the columns for the same column diameter (0,8 m).

Accordingly, the 3 values studied for the area ratio correspond to 3 different unit cells diameters. The related values are shown in Table 3.

Table 3 – Geometric values associated to each area ratio considered

a_c (%)	d_E (m)	d_c (m)	$d_E - d_c$ (m)
5,0	3,6		2,8
11,1	2,4	0,8	1,6
16,0	2,0		1,2

Processing the numerical results obtained for each parameter considered, it was possible to achieve the differential final settlement on the embankment surface for every embankment studied. Accordingly, the follow graphics represent the differential settlement developed at the top of the embankment, plotted against the embankment final height, h_e, and, separately, for each parameter studied. In this way, Figure 4, represents the differential settlements for 3 values of the encasement tensile stiffness, Figure 5 for 3 values of the compressibility of the soft clay, Figure 6 for 3 values of the thickness of the soft clay and, finally, Figure 7 represents the differential settlement for 3 values of the area ratio.

From the results exposed, it can be concluded that the most sensitive parameters affecting the embankment critical height are, effectively, as it was already determined by McGuire (2011) and Sloan (2011), the area ratio. In fact, for the tensile stiffness of the geotextile, compressibility of the soft clay and thickness of the soft clay, the embankment critical height reached for a unit cell of 2,4 m and a column diameter of 0,8 m, was always 2,30 m. Note, from the figures below, that the critical height appears to be 2,00 m. However, the differential settlement is in fact zero, only for 2,30 m of embankment height. So, it is important to focus that, for the embankment height of 2,00 m, the differential settlement is very small but, exists.

For the area ratio parameter, plotted in Figure 4, higher associated values correspond to closer columns with the same diameter, and the embankment critical height, h_{crit}, was found to be smaller in those cases: 1,85 m for $a_c = 16{,}0\%$, 2,30 m for $a_c = 11{,}1\%$ and, finally, 3,35 m for $a_c = 5{,}0\%$

Despite the conclusions associated to the critical height, other interesting findings from the exposed processed results may be commented.

It is important to note that both variation of the encasement tensile stiffness (Figure 4) and thickness of the soft clay layer (Figure 6), directly affect the axial stiffness of the column. The first one, through the confinement provided to the sand material, mobilized by radial deformation of the column, which, consequently, forces the development of increased tensile strains in the geotextile. The last one, through the column length, imposed by a given soft clay thickness.

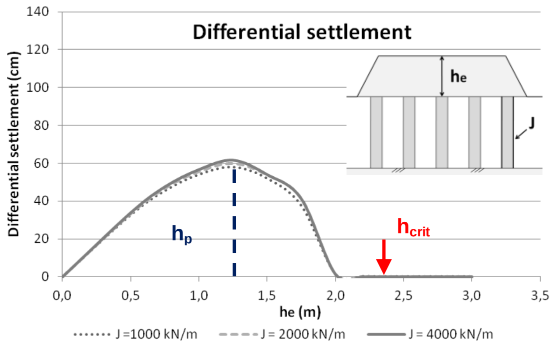

Figure 4 – Differential settlement plotted against embankment height and encasement tensile stiffness

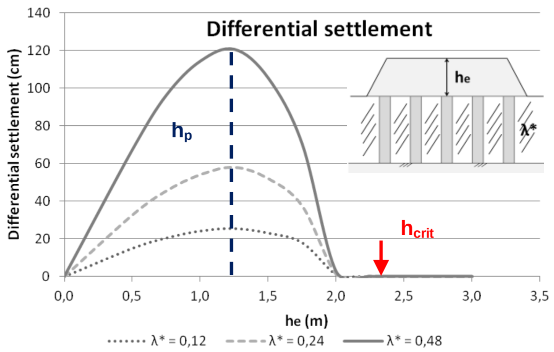

Figure 5 – Differential settlement plotted against embankment height and compressibility of the soft clay

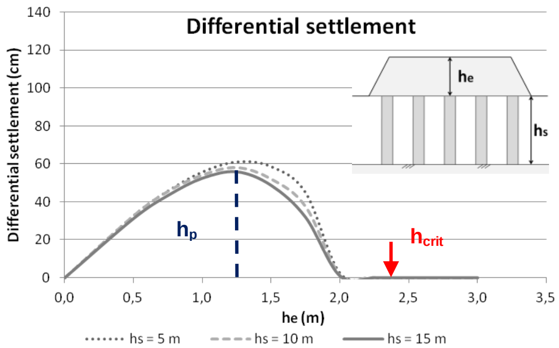

Figure 6 – Differential settlement plotted against embankment height and thickness of the soft clay

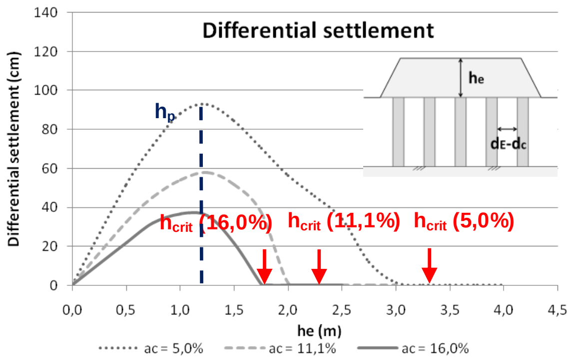

Figure 7 – Differential settlement plotted against embankment height and area ratio

Therefore, from the results obtain for the mentioned parameters, it can be found that the axial stiffness, for a constant column diameter, does not significantly affect the magnitude of the differential settlements. However, note that a higher value of column axial stiffness is associated, as well, to a higher differential settlement developed at the top of the embankment for a given embankment height. This occurs, because stiffer columns experience less deformation under loading, creating, consequently, a higher difference between the vertical deformations of the column and the settlement of the soft soil.

For the two previous parameters, the lateral deformation of the columns, confines the surrounding soil, increasing its bearing capacity. Since the span between the columns is constant, the key factor affecting the differential settlements, for those cases, is the column stiffness.

In the other hand, both compressibility of the soft clay and the area ratio of the system, appear to affect substantially the magnitude of the differential settlement at the embankment surface. In fact, under a given loading, more compressible clays have a low bearing capacity and, in response, develop bigger deformations. Similarly, increasing the span between columns, the soil between columns, under loading, is much more deformable. Note that, in both cases, the confinement provided, from the bulging of the columns, to the soft soil, decreases significantly and the magnitude of the differential settlement is mostly affected by deformations developed at the top of the soft soil.

Additionally, it is curious to found that, in all the studied cases, differential settlement increases for higher embankments until a maximum value, decreasing, then, until the critical embankment height is reached. Therefore, until the maximum differential settlement value is reached, the movements at the embankment base, develops similar settlements at its surface, both over the column and the soft soil. From the maximum value, for higher values of embankment height, the embankment is stiff enough, and the magnitude of the differential settlements at its surface starts to be smaller comparing with the movements occurring at its base, which results in continuous reduction of the differential settlements with the embankment height. This reduction occurs, until the settlements at the embankment base do not produce measurable movements at its surface (critical height). Through this behavior, it was possible to conclude that the development of the critical height is associated to the total mobilization of the arch effect on the supported embankment. In this way, note that the maximum differential settlement value develops always for the same embankment height (1,25 m), defined here as h_p. The p index is related to the developed peak of differential settlements. So it may be found that this value is not significantly affected by the previous parameters. However, the embankment peak height seems to be slightly influenced by the span between columns.

To confirm and to fully understand the development of the differential settlement peak value, an additional study was performed, this time by changing the columns diameter and keeping the span between columns. This study also implies the modification of the area ratio. Accordingly, the values associated to the geometry of the unit cells simulated, are represented in Table 4. The corresponding results in terms of the differential settlements plotted against the embankment height for 3 values of column diameter, are represented in Figure 8.

Table 4 – Geometric values associated to each column diameter considered

d_c (m)	r_c (m)	a_c (%)	r_E (m)	$r_E - r_c$ (m)
1,2	0,60	18,4	1,40	0,8
0,8	0,40	11,1	1,20	0,8
0,5	0,25	5,7	1,05	0,8

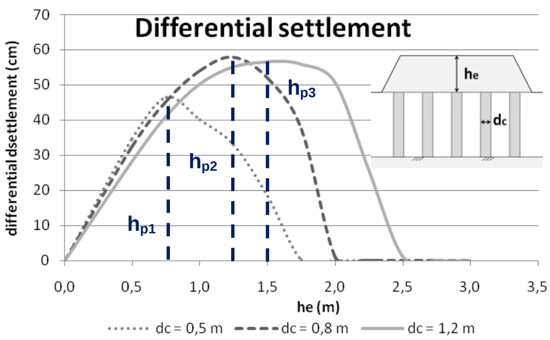

Figure 8 – Differential settlement plotted against embankment height and column diameter

From Figure 8, it is interesting to find out that the columns diameter actually affects de embankment peak height, h_p, for which the maximum value of the differential settlement is achieved. However, since the span between columns is the same, the magnitude of the differential settlements is not significantly affected. Accordingly, it was obtained an embankment peak height of 0,75 m for a column diameter of 0,5 m, 1,25 m for a column diameter of 0,8 m, and, finally, 1,5 m for a column diameter of 1,2 m, which means that, for the same span between columns, the embankment peak height decreases for smaller columns diameters. Note that, once the area ratio changes, the critical height also changes for each considered column diameter. Therefore, from the processed results, it may be found that the embankment peak height is mostly affected by the area of rigid elements (columns) installed in a given soft soil area. Conversely, note that h_p is not affected by changes in the axial stiffness (EA) of columns with the same diameter or by the compressibility of the soft clay. Furthermore, it may be concluded that, similarly to the critical height, the peak height is affected by the area ratio, but in this case, the diameter of rigid elements have a determinant influence on the development of the embankment peak height when compared to the span between columns (area of untreated soil).

5. CRITICAL HEIGHT – DESIGN EQUATION

For the formulation of the proposed design equation, which allows to estimate the critical height function of the area ratio, it was necessary to study the critical height associated to 2 more values. Thus, for a area ratio of 2,5% it was found a critical height of 4,5 m, and for a area ratio of 25% it was found the corresponding value of 1,5 m.

To formulate the equation it was required to consider the layout configuration in which the columns are disposed. Therefore, based on the results achieved by McGuire (2011) for piled embankments, the critical height is a function of the columns diameter, d_c, and the distance, s', from the edge of the circular column to the farthest point from the center of the influence area. The parameter s' is shown in Figure 9 for a variety of mesh configurations defined by the spacing s_1 and s_2.

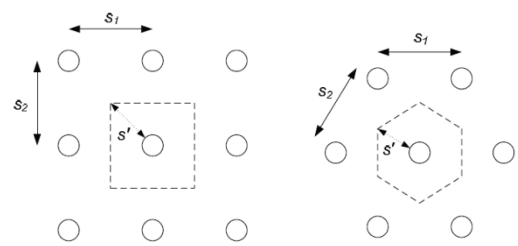

Figure 9 – Rectangular and triangular meshes (Filz *et al.*, 2012)

Note that the numerical values obtained in this work are for a unit cell. Thus, for a unit cell diameter, d_E, its relation with the spacing, s, for a symmetric mesh ($s_1 = s_2$) is given by Eq. [5] and Eq. [6] for a square and for a triangular mesh respectively.

$$d_E = 1{,}13s \qquad [5]$$

$$d_E = 1{,}05s \qquad [6]$$

Accordingly, the distance s' is associated to the influence area of the columns, which depends on their layout: for a square layout, the influence area is also square, while for the triangular layout, the influence area is hexagonal. Therefore, the distance s' is given by Eq. [7] for a square mesh and by Eq. [8] for a triangular mesh.

$$s' = \frac{(2s^2)^{\frac{1}{2}}}{2} - \frac{d_c}{2} \qquad [7]$$

$$s' = \frac{(3s^2)^{\frac{1}{2}}}{3} - \frac{d_c}{2} \qquad [8]$$

Based on these facts, a design equation function of the distance s' and the columns diameter, d_c, may be formulated. The s' values associated to each area ratio are represented in Table 5, while the data used to estimate the design equation are represented in Table 6.

Table 5 – Spacing between columns for a square and for a triangular layout

a_c (%)	d_c (m)	h_{crit} (m)	Square layout		Triangular layout	
			s (m)	s' (m)	s (m)	s' (m)
2,5		4,50	4,42	2,73	4,76	2,35
5,0		3,35	3,19	1,85	3,43	1,58
11,1	0,8	2,30	2,12	1,10	2,29	0,92
16,0		1,85	1,77	0,85	1,90	0,70
25,0		1,50	1,42	0,60	1,52	0,48

Table 6 – Data used to formulate the design equation

a_c (%)	h_{crit}/d_c (-)	Square layout	Triangular layout
		s'/d_c (-)	s'/d_c (-)
2,5	5,63	3,41	2,94
5,0	4,19	2,32	1,97
11,1	2,88	1,38	1,15
16,0	2,31	1,06	0,87
25,0	1,88	0,75	0,60

From Table 5, it is interesting to found that, for a given embankment critical height, it is possible to install columns with a higher spacing, using a triangular layout.

The data represented in Table 6 is graphically shown in Figure 10. The trend line trough the data, is given by Eq. [9] for a square layout and by Eq. [10] for a triangular layout, which were the required design equations for the conclusion of the present work.

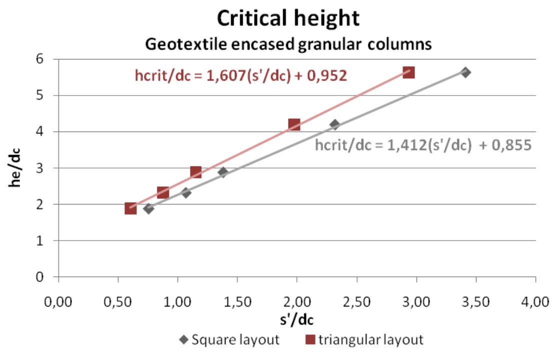

Figure 10 – Critical height for a square and for a triangular layout

$$h_{crit} = 1{,}412s' + 0{,}855d_c \quad [9]$$

$$h_{crit} = 1{,}607s' + 0{,}952d_c \quad [10]$$

6. GEOTEXTILE ENCASED GRANULAR COLUMNS VERSUS PILED EMBANKMENTS

6.1. Numerical analyses

To fully understand the complex behavior of geotextile encased granular columns, it was additionally performed numerical analyses, also through the unit cell concept, this time for very rigid columns. The simulated elements were piles with a linear elastic behavior. The chosen values for the required parameters are represented in Table 7. For the rest of the materials, i.e., embankment, soft clay and for the reinforcement, the constitutive models and their parameters were the same as the ones shown in Table 1.

Table 7 - Constitutive model and properties adopted in PLAXIS 2D for piles

Properties	Pile (*Linear Elastic*)
γ (kN/m^3)	25
E (kPa)	30 x 10^6
ν (-)	0,2
k_x(m/dia)	1x10^{-5}
k_y (m/dia)	1x10^{-5}

From the numerical results obtained, the most important conclusion is that, for the same unit cell modeled, i.e., for the same column diameter and the same span between the columns, the critical height achieved, is almost the same for both columns and piles. On the other hand, the critical height is directly associated to the arch effect. Thus, it can be confirmed that the arch effect, for the same span and column diameter, is not significantly affected by changes in the axial stiffness (EA) of the column, which means, the load attracted to the columns and to the soft soil is mostly affected by the area ratio.

On the other hand, it was confirmed that, higher values of the axial stiffness of the columns slightly increase the magnitude of the differential settlements developed at the top of the embankment. Thus, Figure 11 shows, separately, the settlements developed at the embankment surface, over the columns and over the soft soil. The exposed results are for piles and for columns encased by a geotextile with a tensile stiffness of 1000 kN/m, both for a unit cell diameter of 2,4 m and for a column diameter of 0,8 m. The rest of the parameters used are the ones already presented in Table 2. From Figure 11, it may also be confirmed that the pile material do not settle under load, which means that, over the top of the piles there are no significantly settlements until the embankment peak height is reached. Only for embankments higher than the peak height, their stiffness is enough to produce measureable settlements at their surfaces, over the piles.

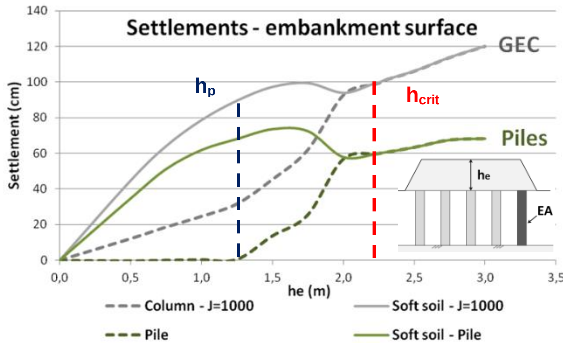

Figure 11 – Settlements at the embankment surface plotted against embankment height for piles and columns with J = 1000 kN/m

Conversely, for embankment heights lower than the peak one, Figure 11 shows that geotextile encased granular columns settle under applied load. In addition it may also be concluded that, although the differential settlements are bigger for piled embankments, the uniform settlement developed at the embankment surface, for embankments with an height higher than the critical height, is bigger for deformable columns. This behavior is due to the interaction developed, between the deformable column and the surrounding soft soil.

From Figure 11, it was also possible to confirm that both of GEC and piles reach, again, the maximum differential settlement for the same embankment peak height of 1,25 m. In addition, from Figure 11, it is, as well, very clear that for embankment heights higher than h_p, there is a clear change in the way how settlements, at the embankment surface, over the column and over the soft soil, are developed.

Finally, these facts confirm that the system composed by geotextile encased granular columns is more flexible and interactive than the piled embankments. Therefore, for geotextile encased granular columns, the behavior of the improved soil, depends on the interaction between de vertical and lateral deformations of the column and the mobilized strength of the geotextile and consequent confinement provided to the soft soil.

6.2. Comparison of results

McGuire (2011) used bench-scale laboratory tests to investigate, among other parameters, the critical height of a piled embankment in a square array, and proposed that the critical height is a function of the column diameter and the distance s', and is given by Eq.[11].

$$h_{crit} = 1{,}15s' + 1{,}44d_c \qquad [11]$$

In the other hand, Sloan (2011) used instrumented field-scale tests also to investigate, among other parameters, the critical height of a piled embankment in a square array. The critical height from Sloan's (2011) field-scale tests is in good agreement with McGuire's (2011) findings. In addition, considerable information is also available from the published literature for other laboratory-scale experiments, other field-scale tests, centrifuge experiments, and full-scale field case histories, for columns or piled embankments, in a square or in a triangular array. In some cases, systematic experiments were done to determine the critical height. In other cases, the critical height was not determined, but differential surface settlements were either reported or not reported. The referred information is presented in Figure 12, where is also represented the processed numerical results obtained for the critical height of geotextile encased granular columns in a square array.

From Figure 12 it may be concluded that, as far as critical height is concerned, there are no significant discrepancies between the results for piled embankments obtained by McGuire (2011) and Sloan (2011), and the numerical results obtained herein for embankments supported by geotextile encased granular columns. However, it is interesting to note that the design equations cross each other for s'/d_c = 2,23 value.

Therefore, for lower values of s'/d_c (<2,23), the reinforcement system using piles, is too rigid and a higher embankment is necessary to mobilized the total arch effect. On the other hand, for higher values of s'/d_c (>2,23), the span between columns increases, and the confinement provided to the soft soil through the lateral expansion of the columns decreases significantly. For these cases, the improvement of the soft soil using geotextile encased granular columns is too flexible and starts to lose its overall efficiency.

It should be pointed out that, for columns installed closed to each other, it is more efficient, to use geotextile encased granular columns and for the opposite, it is better to use the reinforced system using piles. But again, the discrepancies between the design equations for each solution are not significant.

7. CONCLUSIONS

The main purpose of this work was to study the parameters affecting the critical height of an embankment supported by geotextile encased granular columns in soft clay. The unit cell modeling approach was used to perform numerical analyses using the finite element method. Based on the findings obtained for the differential settlements developed at the top of the embankment, the following conclusions may be pointed out.

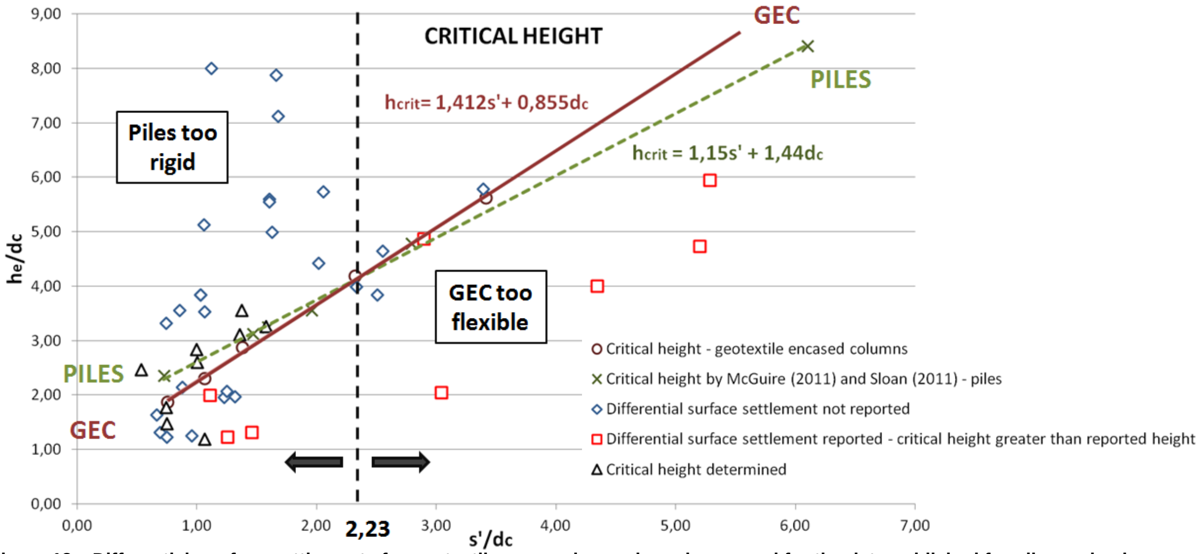

Figure 12 – Differential surface settlements for geotextile encased granular columns and for the data published for piles and columns

1. The embankment critical height is affected by both column diameter and span between columns (area ratio). Also, it was found that critical height is directly associated to the total mobilization of the arch effect at the embankment base;
2. The embankment peak height depends, as well, on the area ratio. However, the area of the columns (column diameter) was found to be much more influent than the area of untreated soft soil (span between columns);
3. The magnitude of the differential surface settlements, are significantly affected by the compressibility of the soft clay and by the span between columns (deformations developed at the top of the soft soil). Conversely, column's axial stiffness (EA) do not affect significantly the magnitude of the differential surface settlements;
4. Soft soil improvement using geotextile encased granular columns technique was found to be a more flexible system than the one associated to piles. Thus, the bearing capacity of the first one, is mobilized through the developed interaction between the lateral deformation of the columns and the consequent confinement of the surrounding soil;
5. It may be concluded that as far as critical height is concerned, there are no significant discrepancies between the piled embankment and the embankment supported by GEC's in a soft clay;
6. Finally, it was additionally found, by the performed numerical analyses obtained, that the horizontal reinforcement acting on the base of the embankment, for the unit cell simulated, and for the value used for the column stiffness, does not appear to support any loads acting over the top of the soft soil. However, this reinforcement should have a great importance for the uniformization of the embankment settlements.

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