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CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

E-ISSN 2450-8594

CEER 2020; 30 (3): 0234-0252
DOI: 10.2478/ceer-2020-0042
Original Research Article

CONTRIBUTION TO THE STUDY OF SOIL STABILIZED BY BALLAST COLUMNS

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Abstract

Ballasted columns are an interesting technique for improving compressible soils in situ. Their major advantages are to reduce compaction, increase the bearing capacity of soils, accelerate consolidation, and eliminate the risks of liquefaction during earthquakes. Thanks to these advantages, reinforcement processes are considerably developed in the field of geotechnical construction and this is on an international scale.

Numerical modelling is a necessary and effective alternative for approaching the real behavior of soils reinforced by ballasted columns. The present work aims to change several parameters, being, among others, the number of columns, the rise of the water table, and the friction angle. With this in mind, a parametric study was carried out in order to determine the influence of certain parameters on the settlement results and observe their influence on the mechanical behavior of the soil using the **Plaxis 2D** calculation code.

This study found that the correct choice was based on the number of columns, which is three, while the increase in groundwater level does not have a significant influence on the results.

Keywords: ballasted, column, displacement, forced, finite element, granular, improvement, inclusion, soil

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1. INTRODUCTION

Humans do not have any direct control over the process of soil formation. The existing soil on a given site may not be suitable for supporting the desired facilities such as buildings, bridges, and dams, because the bearing capacity of a given soil may not be adequate to support the required load. To improve soil types in order to allow building and other heavy construction, it is necessary to create stiff reinforcing elements in the soil mass. A number of these techniques have been developed in the last 50 years [1].

The mechanics of ground improvement depends largely on the type of soil. Granular soil such as sand and gravel in loose condition has low shear strength. A variety of methods are available to improve the granular soils, including compaction piles [2, 3], vibrocompaction [4, 5], and dynamic compaction [6]. Soft clay deposits are extensively located in many areas and exhibit poor strength together with high compressibility.

Soil improvement techniques consist of modifying the characteristics of a soil by extending vibroflotation to soils that have silty or clay layers, the elements of which cannot be rearranged by vibration. The ballasted columns make it possible to treat these soils by incorporating granular materials (commonly called ballast) compacted by rising passes. These columns can also be cemented or made of mortar, or included in the soil by mixing the soil with a more resistant material in order to [1, 4, 7]:

- Increase bearing capacity and / or shear strength,
- Reduce the settlements, both absolute and differential, and if necessary accelerate them,
- Reduce or eliminate the risk of liquefaction in the event of an earthquake or major vibrations.

The fields of application of the various techniques depend essentially on the nature and the granulometry of the ground which one wishes to improve.

The literature generally deals with the justification of the bearing capacity of the ballasted columns and the estimate of the settlements of the reinforced site under the load applied by the project. The commonly accepted assumption is that the column is in a state of triaxial stresses. Different hypotheses are used to define the state of confinement of the column by the ambient soil. They are most often based on the use of the coefficient of land at rest K_0 [7, 8, 9].

The main objective of this work is to contribute to the study of the inclusion of columns in poor soil by changing several parameters (number of columns, loading intensity, effect of the slick, etc.) and to see their influence on the ground from the standpoint of settlement.

2. BEHAVIOUR MECHANISMS

The operating mechanisms of the ballasted columns depend on [2, 10]:

- Column layout, single column or group;
- Loading mode, rigid or flexible foundation;
- The type of column (anchored or floating).

This is primarily a question of distinguishing the general principles which govern the operation of the ballasted columns in the broader sense, then the mechanism of operation and rupture, and that the settlement is due to the compaction of material. As soon as a column expands laterally, the area of elastic deformation is assumed to be exceeded and one therefore enters that of plastic deformation. It is thanks to these two movements that the column transmits part of the stresses to the surrounding soil [3].

The lateral containment power is all the more marked since the columns are in groups, so that two columns provide a lateral embrace allowing them to undergo less significant deformations. Indeed, it has been noted that for columns arranged in groups, as adjacent columns are built to form the group, the columns located inside are confined and thus stiffened by the surrounding columns [3].

3. MODELING OF A NETWORK OF BALLAST COLUMNS

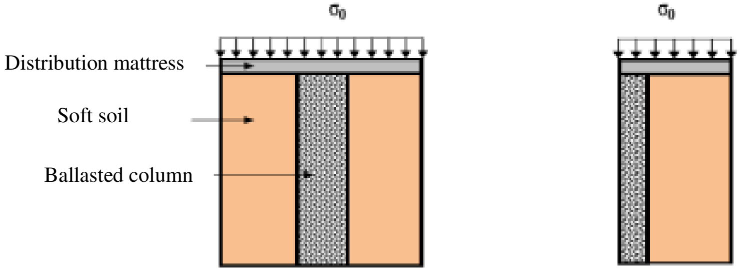
3.1. Introduction

Bibliographic synthesis has shown that many approaches can be envisaged for the calculation of networks of ballasted columns. In this chapter, we propose calculating a network of columns ballasted by finite elements in the case of a model based on the concept of the composite cell "ballast-soil"[10].

We first present the adopted calculation model, specifying the parameters and the modeling hypotheses used. Then, the analysis of the results makes it possible to better understand the mechanical behavior of this system, and to identify in detail the interactions involved during loading. The sensitivity of the various parameters involved in sizing is also studied.

On the basis of this model, a parametric study is carried out for different substitution rates (A / Ac), Ec / Es ratios and loading levels ∇q [11].

3.2. Recommendation of DTU 13.2



a) Model of an elementary cell b) Axisymmetric model

Fig.1. Introducing the model of the ballast column

D.T.U 13.2 [12] states that a ballast column is always capped by a granular layer or distribution mattress. This mattress is built to distribute vertical stresses on the head of the ballast column. Here, during the installation of the column element, the upper and lower sides of the model are blocked to simulate the vertical containment of a deep layer [12].

3.3. Parametric study

A parametric study was carried out to determine the influence of certain parameters on the settlement results. From a basic model, for which the set of mechanical properties of the materials is defined in Table 1, we varied certain parameters. Indeed, the parameters which were the subject of this parametric study are likely to vary according to the site location and time (short or long term parameters of the materials), the nature of the ballast (Young's modulus and angle of friction of the ballast) as well as according to the embodiment of the column (interface between the column and the ground). For all these parameters we:

Calculated the soil compaction before and after treatment according to either the Priebe method or the theory of elasticity, according to the Plaxis 2D calculation code;

1. Calculation of horizontal displacements;
2. Calculation of stresses in the soil;
3. Work with 1, 2, and 3 columns.

3.4. Geometry of the digital model

Numerical modeling was performed using the PLAXIS 2D program. PLAXIS is used for the analysis of deformation and stability in geotechnical engineering. The improved soil is modeled with 15 nodes of triangular finite elements. In the numerical analysis, medium mesh was used; however, in the reinforced area, the medium mesh was refined to allow for the fact that stresses and displacements are higher in this area [1].

A geometric model (2D) 15 m wide by 15 m deep was defined as follows: A circular foundation (strike off) 4m in diameter and 0,25 m thick, resting on a layer of soft clay 10 m thick, reinforced by ballasted columns [03 columns], and a load transfer mat arranged between the network of columns and the foundation, as shown Figure 2.

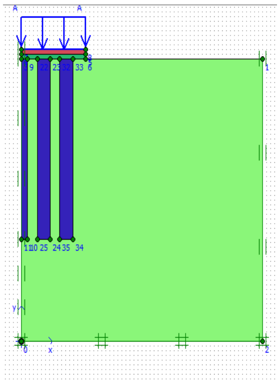
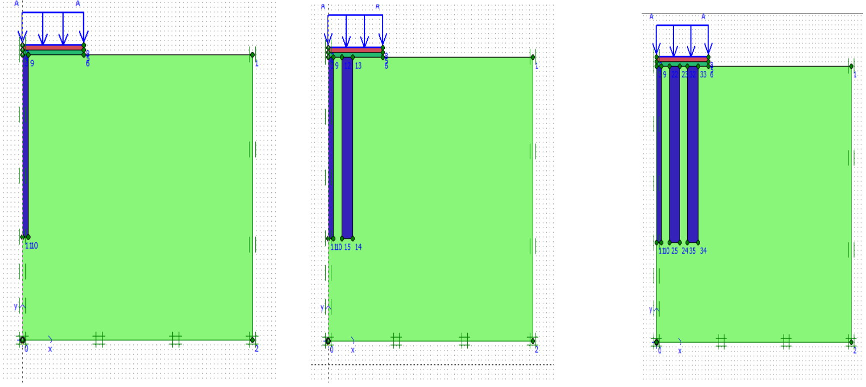


Fig. 2. Model of ballasted column subjected to a distributed loading

It is assumed that the circular foundation is subjected to an average distributed force $\nabla q=120kN/m^2$.

3.5. The effect of the number of columns

In order to understand the interactions between ballast columns and the surrounding soil, columns (1,2, and 3 columns) will be implanted in the ground as shown in Figure 3.



a. One column b. Two columns c. Three columns

Fig.3. Implantation of ballast columns

3.6. Generation of mesh

One of the strengths of the Plaxis 2D program is that the mesh can be generated automatically. The operator can set the fine mesh at different levels (very coarse, coarse, medium, fine, very fine) [1].

The reference model is made of elements at 15 knots, and an overall finesse (Global coarseness) of < coarse> is deemed optimal, as indicated in Figure 4.

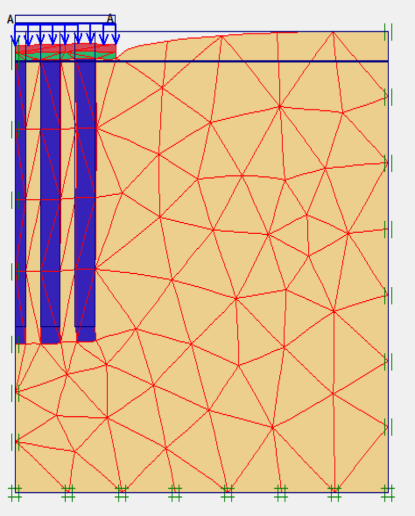


Fig. 4. Networking generation of the geometric model

4. CHARACTERISTICS OF THE MATERIALS USED

Appropriate choices of material properties are necessary in order to have an accurate simulation of the reinforcement system in the numerical modeling. The properties of the soft clay, the load transfer mattress, ballasted columns, and circular foundations are drawn (strike off) in the literature [13]. A drained behavior is assumed for all the materials.

4.1. Properties of the soft clay layer

Table 1. Properties of the soft clay layer

	Name	Soft clay	Units
Typical model	Model	Mohr-Coulomb	-
Type of behavior	Type	Drained	-
Saturated volume weight	sat	17	kN/m^3
Unsaturated volume weight	unsat	20	kN/m^3
Horizontal permeability	Kx	10-5	m/day
Vertical permeability	Ky	10-5	m/day
Young's Modulus	Eref	4000	kN/m^2
Poisson coefficient	ν	0,35	
Cohesion	C	5	kN/m^2
Internal friction angle	Φ	5°	°
Expansion angle	Ψ	0°	°
Interface rigidity factor	R inter	0,5	-
Width of soft clay layer	X couche	20	M
Depth of soft clay layer	Y couche	10	M

4.2. Properties of the load transfer mattress

The properties of the load transfer mattress are summarized in Table 2 [13].

Table 2. Properties of the load transfer mattress

	Name	mattress	Units
Typical model	Modèle	Linear-elastic	-
Type of behavior	Type	Non poreu	-
Volume weight		22	kN/m^3
Young's Modulus	Eref	50000	kN/m^2
Poisson coefficient	ν	0,30	
Rigidity factor	Rinter	0,5	-
Thick mattress	Em	0,25	M

4.3. Properties of ballasted columns

The properties of the ballasted columns are summarized in Table 3 [13].

Table 3. Properties of the ballasted columns

	Name	columns	Units
Typical model	Model	Mohr-Coulomb	-
Type of behavior	Type	Drained	-
Saturated volume weight	sat	16	kN/m^3
A saturated volume weight	unsat	18	kN/m^3
Horizontal permeability	Kx	10-3	m/day
Vertical permeability	Ky	10-3	m/day
Young's Modulus	Eref	55000	kN/m^2
Poisson coefficient	ν	0,33	
Cohesion	C	1	kN/m^2
Internal friction angle	Φ	38°	°
Expansion angle	Ψ	0°	°
Interface rigidity factor	Rinter	0,5	-
Column diameter	Dcolonne	0.8	M
Column anchor length	Lcolonne	9,60	M
Spacing between columns	Ecolonne		M

4.4. Properties of the circular foundation drawn (strike off)

The properties of the foundation are summarized in Table 4 [13].

Table 4. Circular foundation properties (strike off)

	Name	**Foundation**	**Units**
Typical model	Model	Linear elastic	-
Type of behavior	Type	Non poreu	-
Concrete volume weight	24		kN/m^3
Young's Module	E ref	32000	kN/m^2
Poisson coefficient	ν	0,25	
Interface rigidity factor	Rinter	0,5	-
The thickness of the foundation	Ef	0,25	M

5. RESULTS OBTAINED

In order to understand the interactions between ballasted columns and the ground, we were interested in the following results which can be drawn from this modelling of 1, 2, and 3 columns: settlement, vertical displacement, horizontal displacement, vertical stress, and the axial force for each set of figures (ground without column, and with 1, 2, and 3 columns).

5.1. Vertical displacements: (Settlements)

Vertical movements determined from PLAXIS 2D based on the **Priebe** method [14] are presented in Figure 5. Based on the original parameters of the materials (Table 1,2,3, and 4), different calculations were made by varying [14]:

- The rubbing angle of the ballast
- Young's modulus of the ballast
- Young's modulus for limey clay

For a medium stress $\nabla q=120$ KN/m^2, the settlements obtained are summarized in table 5.

Table 5. Settlements

	1 column	**2 columns**	**3 columns**
Settlement before treatment (mm)	220,67	220,67	220,67
Settlement after treatment (mm)	208,43	150,25	101,67

For soil without any columns, settlement is significant, on the other hand, as the columns are installed, this settlement decreases markedly, as can be seen for 3 columns, which represents the best choice.

5.2. Horizontal displacements

The same is true for the horizontal displacement, which has its minimum value for 3 columns.

Table 6. Horizontal displacements

	1 column	**2 columns**	**3 columns**
Dipl. horizontal before treatment (mm)	25,35	25,35	25,35
Dipl. horizontal after treatment (mm)	24,72	18,47	11,88

5.3. Effect of the water table

In the calculation phase, we can also modify the level of the water table as well as certain properties of the materials. In this study, this modification consisted of raising the level of the water table to 8.6 m. After the modification, we obtained the following results [15,16]:

5.3.1. Settlements

For a medium stress $\nabla q=120$ KN/m^2, and the water level at 9 m below the lower column base, the settlements obtained are summarized in table 7.

Table 7. Settlements

	1 column	**2 columns**	**3 columns**
Settlement before treatment (mm)	220,78	220,78	220,78
Settlement after treatment (mm)	209,84	156,45	108,90

Settlement levels in this case are almost the same as the settlement levels without water, so the effect of the water table on the vertical (settlement) and horizontal displacement either did not change or its level remained at the base [15, 16].

5.3.2. Horizontal displacements

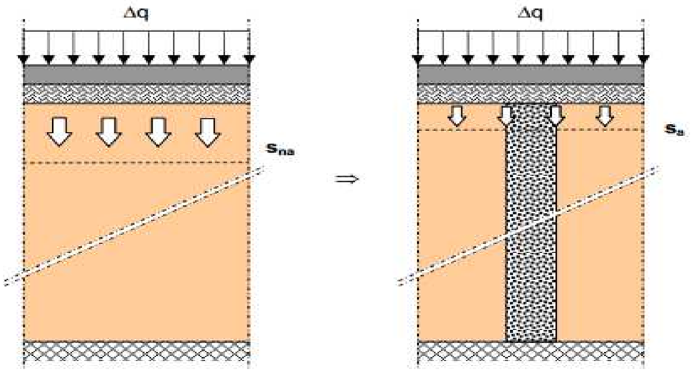
Similarly for the horizontal displacement, raising the water level gives the minimum value for 3 columns.

Table 8. Horizontal displacement

	1 column	**2 columns**	**3 columns**
Horizontal displacement before treatment (mm)	25,49	25,49	25,49
Horizontal displacement after treatment (mm)	24,88	20,17	12,18

5.4. Influence of parameters on the improvement factor β

5.4.1. Influence of loading Δq on the improvement factor β



Untreated soil

Treated soil

Fig. 5. Settlement of treated and untreated soils

Figure 5 makes it possible to observe the evolution of the parameter β for the model, characterizing the effectiveness of the treatment (improvement factor). This parameter is expressed as the ratio of unimproved soil settlement (without column) to improved soil settlement (with column). The improvement factor (the effectiveness of the treatment) β is given by the formula [4, 14, 17]:

$$\beta = \frac{S_{na}}{S_a} \tag{5.1}$$

Sna : the average settlement due to loading Δq on untreated soil, Sa : the settlement obtained after reinforcement.

Abbreviation used:

SST : soil compaction without treatment.

SAT : soil compaction with treatment (1 Column, 2 Columns, and 3 Columns).

In the case of rigid foundations, the settlements are identical at the column head and, in the case of soft foundations, they differ little on the surface of the ground [4].

Balaam and Poulos [14, 18] indicated that the reduction factors of settlement under flexible and rigid structures differ only by five percent for common processing geometries.

Table 9. Values of soil settlements before and after treatment, and values of β

Load(KN /m^2)	**SST (mm)**	**1CSAT (mm)**	**β**	**2CSAT (mm)**	**β**	**3CSAT (mm)**	**β**
20	44,73	39,72	1,126	25,57	1,749	15,28	2,927
40	79,86	73,04	1,093	47,95	1,665	30,98	2,577
60	114,97	106,59	1,078	71,04	1,618	47,83	2,403
80	150,10	140,31	1,069	96,38	1,557	65,14	2,304
100	185,31	174,14	1,064	122,85	1,508	82,94	2,234
120	220,67	208,43	1,058	150,25	1,468	101,67	2,170
140	260,52	246,25	1,057	178,66	1,458	122,48	2,127
160	317,98	294,76	1,078	209,79	1,515	144,53	2,200
180	397,03	362,09	1,096	244,72	1,622	167,83	2,365
200	499,88	450,29	1,110	285,58	1,750	191,84	2,605

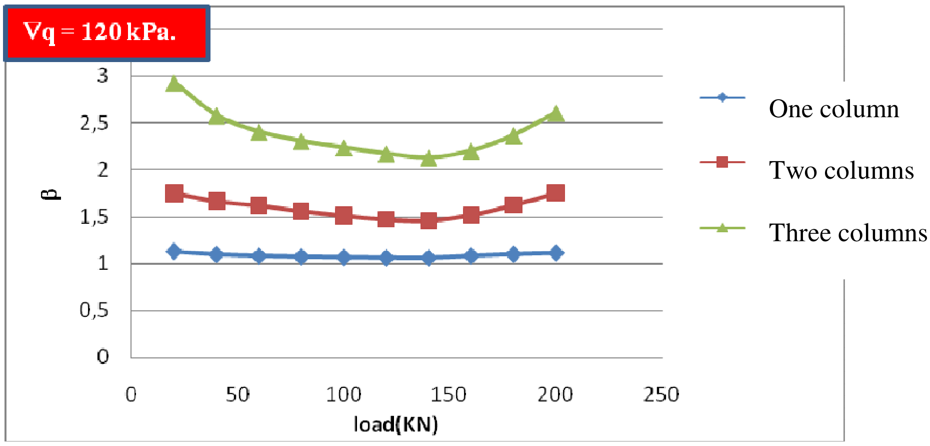


Fig. 6. Soil improvement factors β with the variation of ϕc
(for 1C, 2C, and 3C)

One can conclude that the value of β changes appreciably with the intensity of the loading.

5.4.2. Influence of the friction angle φc

Insofar as the failure criterion adopted is the Mohr Coulomb criterion, the friction angle of the ballast constitutes a parameter involved in the dimensioning. In the case of a load, ∇q = 120 kPa. The results of settlements and β are given in table 10 and figure 7.

Table 10. Values of soil settlements before and after treatment, and values of β

ϕc (°)	**SST (mm)**	**1CSAT (mm)**	**β**	**2CSAT (mm)**	**β**	**3CSAT (mm)**	**β**
38	220,67	208,43	1,058	150,25	1,468	101,67	2,170
40	220,67	207,34	1,064	146,47	1,506	99,6	2,215
42	220,67	206,47	1,068	142,51	1,548	98,37	2,243
44	220,67	205,06	1,076	139,37	1,583	97,52	2,262

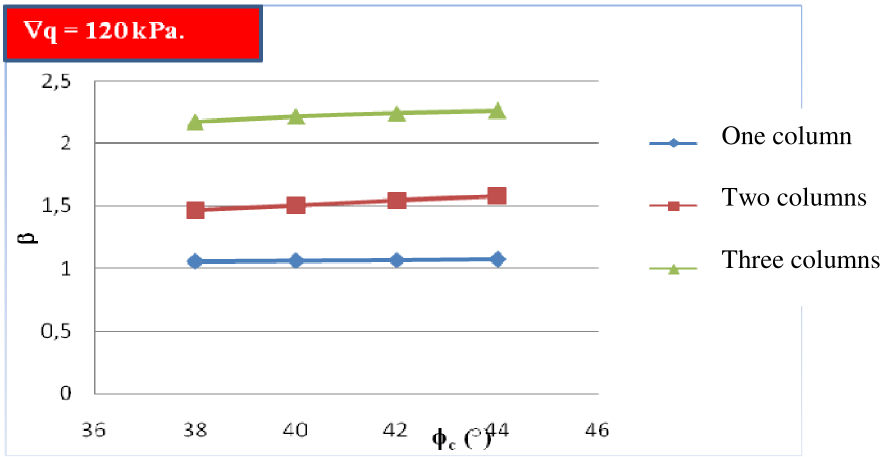


Fig.7. Soil improvement factors β with the variation of ϕc
(for 1C, 2C, and 3C)

Figure 7 shows, for values of ϕc between 38° to 44°, that the best soil improvement is obtained with the highest value of ϕc and for 3 columns. The improvement is also noticeable since b changes from 2.17 for ϕc = 38° to 2.262 for ϕc = 44°.

5.4.3. Influence of the dilatancy angle ψc

The previous results were obtained for a dilatancy angle ψc of zero, that is to say for a ballast material considered to be non-expanding. The angle φc retained is 38°.

Table 7 and figure 7 show the influence of the dilatancy angle ψc on settlements and improvement factors β.

Table 11. Values of soil settlements before and after treatment, and values of β

Ψc (°)	SST (mm)	1CSAT (mm)	β	2CSAT (mm)	β	3CSAT (mm)	β
0	220,67	208,43	1,058	150,25	1,468	101,67	2,170
10	220,67	207,57	1,063	148,03	1,490	100,49	2,195
20	220,67	206,79	1,0671	146,12	1,510	99,47	2,218
30	220,67	205,76	1,0724	144,1	1,531	98,75	2,234

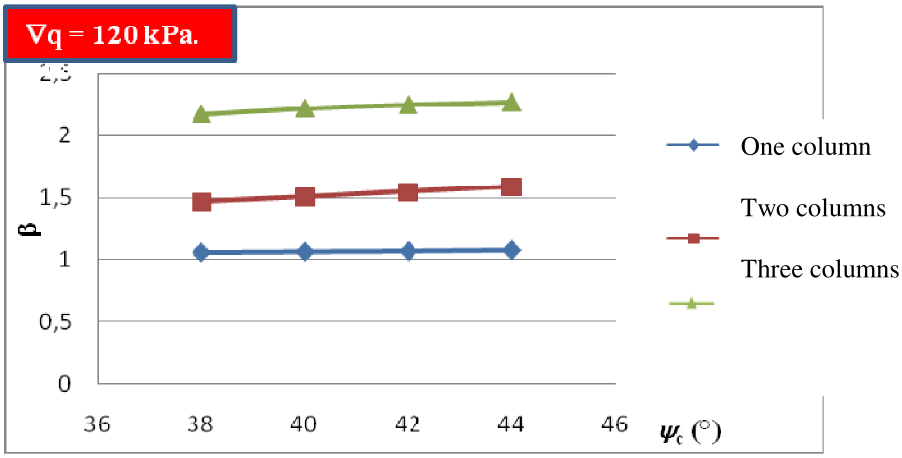


Fig. 8. Soil improvement factors β with variation in Ψc
(for 1C, 2C, and 3C)

Figure 8 shows the influence of the dilation angle on the improvement factor β, which goes from 2.17 for ψc = 0 ° to 2.23 for ψc = 30 ° for the improvement with 3 columns. As per the other test results, improvement is more effective with 3 columns.

These values remain theoretical because, in practice, the dilatancy angle does not exceed 15 to 20°.

5.4.4. Influence of the modulus of elasticity ratio Ec/Es

Figure 5 shows the evolution of the improvement factor β according to the ratio of the elasticity modules Ec / Es for the same loading (Δq = 120 kPa).

In this case, the elastic solution is no longer suitable. This is highlighted by Besançon [3] in his analysis of the computational parameters involved in the dimensioning of ballast columns.

Table 12. Values of soil settlements before and after treatment, and values of β

Ec/ Es	SST (mm)	1CSAT (mm)	β	2CSAT (mm)	β	3CSAT (mm)	β
5	220,67	820,63	0,268	558,05	0,395	351,44	0,627
10	220,67	414,03	0,532	288,1	0,765	183,29	1,203
20	220,67	208,43	1,058	150,25	1,468	101,67	2,170
40	220,67	105,76	2,086	79,73	2,767	61,35	3,596

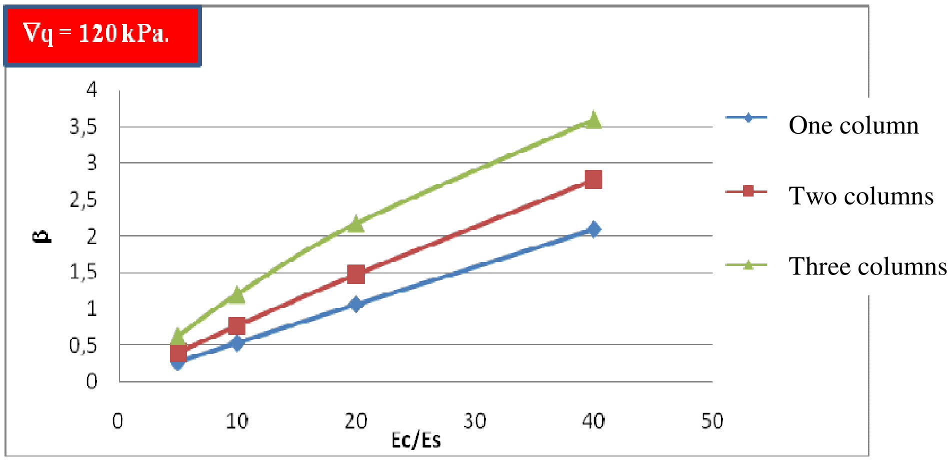


Fig. 9. Soil improvement factors β with variation in E_C/ E_S
(for 1C, 2C, and 3C)

Figure 9 shows the influence of the ratio of the elasticity modules Ec / Es on the improvement factor β for the same loading ∇q = 120kPa. It can be seen that, for (Ec/Es) = 5, the values of β are very close for the three solutions (1 column, 2 columns, and 3 columns), while, beyond 10 for the (Ec/Es) ratio, the values of β are very different and far apart. Again, it is clear that the best solution for improvement is 3 Columns.

5.4.5. Influence of the ratio L/Dc

The ratio L/Dc is varied = (4, 8, 12, and 16)

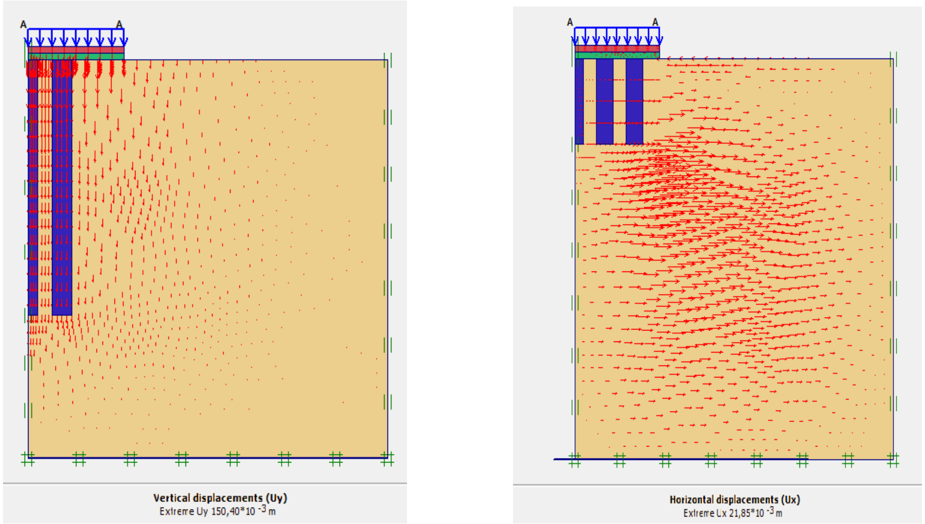


Fig. 10. Some examples of modelling for the report case L/Dc

The table summarizes the settlement values and the values of β for L/Dc ratios.

Table 13. Values of soil settlements before and after treatment, and values of β

L/Dc	SST (mm)	1CSAT (mm)	β	2CSAT (mm)	β	3CSAT (mm)	β
4	220,67	210,95	1,046	175,64	1,256	159,52	1,383
8	220,67	209,31	1,054	158,12	1,395	120,52	1,830
12	220,67	208,43	1,058	150,25	1,468	101,67	2,170
16	220,67	208,11	1,060	145,05	1,521	89,77	2,458

We note that, for the same loading ∇q = 120kPa, the treatment efficiency factor β increases slightly with the length of the column for the 1 and 2 column solutions, but with a very marked increase for 3 columns, where β varies from 1.383 for L/Dc = 4 to 2.458 for L/Dc = 16.

It can be concluded that the processing efficiency factor β is better for a tall column than for lower height, and this also caused lateral stresses which increase with depth.

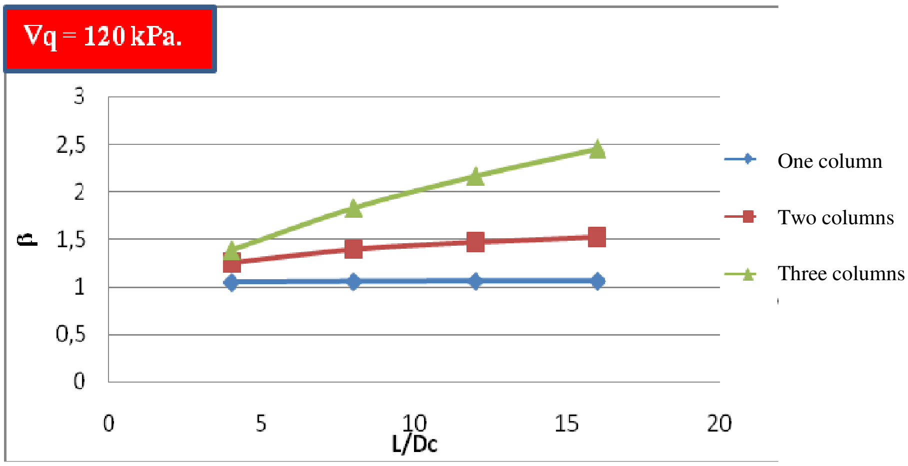


Fig.11. Soil improvement factors β with the variation of L / DC
(For 1C, 2C, and 3C)

5.4.6. Influence of coefficient K_0

Insofar as the performance of a ballasted column depends on the lateral embrace (lateral constraint) that can be mobilized, it is interesting to observe the evolution of parameter β as a function of it. For this, it was decided to involve the coefficient of earth pressure at rest; K_0, defined as follows [8, 17]:

$$\sigma_{h,0} = K_0 . \sigma_{v,0} \tag{5.1}$$

With:

$\sigma_{v,0}$: Vertical constraint,

$\sigma_{h,0}$: lateral constraint,

K_0: coefficient of earth pressure

Table 14. Values of soil settlements before and after treatment, and values of β

K_0	SST (mm)	1CSAT (mm)	β	2CSAT (mm)	β	3CSAT (mm)	β
0,5	220,67	208,49	1,058	150,36	1,467	102,62	2,150
0,6	220,67	208,55	1,058	150,4	1,467	103,63	2,129
0,7	220,67	208,62	1,057	150,44	1,466	104,57	2,110
0,8	220,67	208,61	1,057	150,58	1,465	105,44	2,092
0,9	220,67	208,63	1,057	150,64	1,464	106,39	2,074
1	220,67	208,66	1,057	150,78	1,463	107,37	2,055

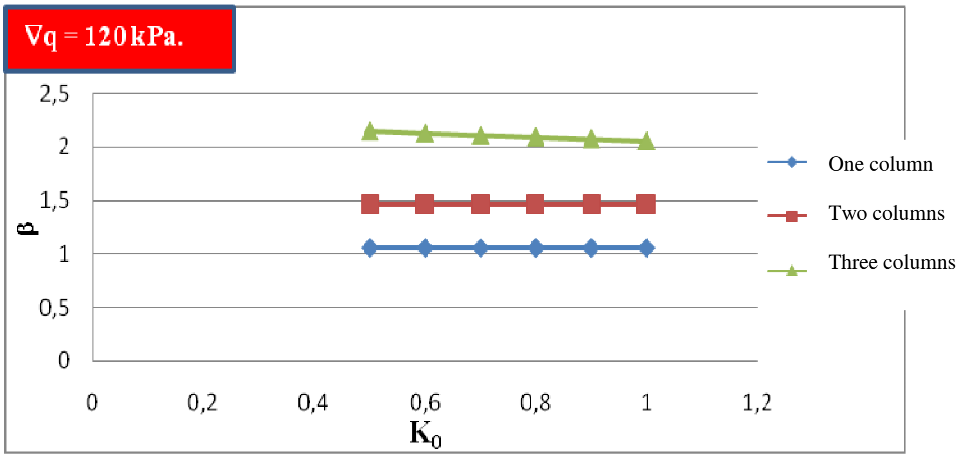


Fig.12. Soil improvement factors β with K_0 variation
(for 1C, 2C, and 3C)

According to the theory, for reasons of the conditions of execution of the columns, the K0 coefficient adopted can vary between 0.5 and 1 [1, 8, 16].
We find from the graph that β increases with the value of K_0, and with regard to the processing efficiency, the solution of 3 columns is once again the best [1].

4. CONCLUSION

After 2D numerical modelling of an axisymmetric model of rigid radius, and a distribution mattress of granular material resting on a poor soil (soft clay) reinforced by a network of ballast columns (3 columns), we have sufficient results to conclude that the implantation of the columns presents an effective solution for soil improvement and that three columns presents the best results for our study, as evidenced by the increase in the soil improvement coefficient β.

- The numerical study carried out on the reference model has led to a better understanding of the behavior of a ballast column and to better define the sensitivity of the parameters involved in the dimensionization of a network;
- Loading, column numbers, column length, and many other parameters affect the weighting and, thus, the value of the improvement coefficient β;
- The presence of the column has increased the carrying capacity of the improved soil and reduces settlements relative to natural soil. These Improvements depend on the constraints applied;
- The K0 coefficient has a significant influence on the value of β. A high value of K_0 generates a better lateral strain of the [column] spine and, therefore, a more efficient treatment;

- Variation of the stress in soft soil with distance from a column is significantly reduced after the installation of a column.
- The inclusion of three columns has yielded the best results and, therefore, it is no longer the larger number that gives the right solution.
- The rise of the slick slightly influenced the movement values.
- The soil improvement factor β evolves with loading, and with the installation of 3 columns.

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Editor received the manuscript: 20.07.2020