Designing reinforced soils by columns

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ABSTRACT
The design of foundations on reinforced ground by columns usually involves two verifications, first, the bearing capacity and, second, the settlement. This contribution details a comprehensive methodology for determining the optimized improved area ratio to avoid overestimated quantities of material columns. The basis of suggested methodology consists in estimating, first, a minimum improvement area ratio (IAR) complying with the allowable bearing capacity of reinforced soil; then a maximum IAR is derived from the verification of allowable settlement. A tank project is analyzed to show up that the use of novel methodology of design, which has been incorporated in recently developed software for the design of reinforced soil by columns, avoids an overestimated reinforcement.

RÉSUMÉ
Le dimensionnement d'une fondation sur sol renforcé par colonnes inclut, en premier lieu, la vérification de la capacité portante, et, en second lieu, la vérification du tassement. Cette contribution présente une nouvelle méthode de détermination du taux d'incorporation optimal permettant d'éviter la sur estimation de la quantité du matériau constitutif des colonnes. Une valeur minimale du taux d'incorporation est identifiée suite à la vérification de la capacité portante admissible; suivie de l'estimation d'une valeur maximale du taux d'incorporation découlant de la vérification du tassement admissible. Un projet de réservoir est exposé pour montrer que la mise en oeuvre de la nouvelle méthodologie de dimensionnement qui a été incorporée dans le logiciel conduit à un gain sur le coût du renforcement.

1 INTRODUCTION

It is well known that the reinforcement of weak soils by columns aims to the increase of bearing capacity, the reduction of settlement, the acceleration of consolidation of soft soils by drained material column and the prevention of liquefaction risk especially in the case of saturated loose sands. The cost of schemes for reinforced soil (RS) foundation using stone columns, compaction piles or deep mixing technique is essentially controlled by the volume fraction of incorporated material as referred to the improvement area ratio (IAR). The Improvement Area Ratio (IAR) is defined by the total cross section of columns divided by the area of loaded foundation.

Weak soils often have very low strength and stiffness characteristics. This category of soil basically includes, high compressible soils of undrained shear strength less than 30 kPa, Young modulus lower than 2 MPa and loose sands having a friction angle less than 30° (i.e. SPT < 10).

Depending on the adopted columnar reinforced technique the IAR ranges from:

- 0.15 to 0.35 for stone columns; the strength of column material is mainly characterized by a high friction angle (i.e. greater than 40°).
- 0.2 to 0.7 for deep mixing; the strength of column material is mainly characterized by enhanced cohesion (twenty times or more than that of initial soil).
- 0.05 to 0.15 for vibro compaction, with or without added material; the strength of column material is characterized by moderate cohesion and enhanced friction angle.

The design of foundations on reinforced ground by columns usually involves the verifications, first, of bearing capacity and, second, of settlement. The design can also involve the acceleration of consolidation when columns behave like vertical drains and the liquefaction potential in case of loose saturated sands.

The existing methods often aim to one verification either bearing capacity or settlement by adopting the unit cell model. Further, existing methods were formulated for a unique type of column installation technique i.e. stone columns (Priebe, 1995), (French standard, 2005) or deep mixing (Broms, 2000), etc.

In these contributions the IAR was only considered as a given data, therefore the optimization of quantity of column material was not discussed. Note the IAR is not taken into account by the French standard to estimate the bearing capacity of RS by the isolated column model. Further, regardless the column installation technique or the modelling of RS, none of the previous methods of design took into account both the bearing capacity and settlement verifications.

In order to suggest a comprehensive design procedure, this paper presents a novel methodology that includes the verifications of bearing capacity and settlement. More else, the suggested methodology considers the results of recent research that were obtained in well stated frameworks.

This methodology of design is detailed for reinforced soils by end bearing and floating columns. The constituents of reinforced soil, i.e. the initial soil also called weak soil and reinforcing columns are identically modelled as a three dimensional medium. The reinforcing columns are located in arbitrary arrangement under the loaded foundation. This methodology is undertaken in three steps to derive an optimized IAR. Therefore, the use of group of columns model made it possible the use of IAR as key parameter for the purpose of design.

By performing the suggested methodology of design the gain in cost is shown for a tank foundation resting on loose silt sand reinforced by end bearing stone columns.

2 STATEMENT OF THE PROBLEM

As for any type of foundation the design of RS by columns starts by the verification of bearing capacity which is a necessary condition, then it follows the verification of settlement that is sufficient to conclude about the stability of studied foundation. Reinforcement is done by vertical either end-bearing or floating columns, of length H_c, installed under loaded area, as referred to foundation (Fig.1). The location of columns of circular cross sections can be arbitrary and their diameter as well (Fig. 2).

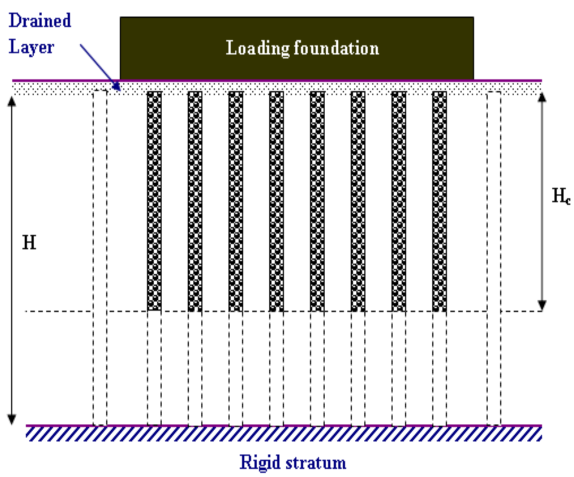
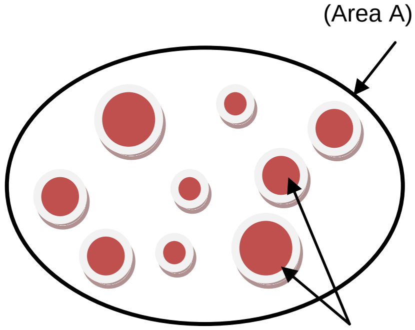


Figure 1. Foundation on reinforced soil by columns

The verification of bearing capacity is predicted by considering the unit weight, friction angle and cohesion of the initial soil and columns material. The settlement is estimated by using the Young modulus and Poisson's ratios of columns material (E_c, ν_c) and weak soil (E_s , ν_s). Since the reinforcement aims to the increase of weak soil's stiffness then: $E_c > E_s$. Lower and upper bounds of ultimate bearing capacity, obtained by limit analysis approaches, are considered to determine the minimum IAR that characterizes the needed reinforcement complying with the allowable bearing capacity of RS.

Foundation
(Area A)



Circular columns
(Total area A_c)

Figure 2. Geometry of foundation and columns location

Second, by the linear elasticity framework an upper bound of settlement is derived after the determination of a lower bound of apparent modulus of RS. Then, on the basis of given allowable settlement of RS a maximum IAR is identified.

Third, an iterative calculation of settlement is carried out to find the optimized IAR. By consequence, the corresponding design of columnar reinforced foundation cannot be qualified as overestimated.

The methodology here presented applies for all types of foundation (rafts, footings, and embankments) shaped rectangular or circular, resting on end-bearing or floating columnar soil. The prediction of bearing capacity here presented, in case of purely cohesive soil reinforced by cohesive frictional column material,

3 BEARING CAPACITY VERIFICATION

In the framework of limit analysis a lower bound, Q^{-}_{ult}, of the ultimate load of a foundation on RS is determined. by performing the static approach (Salençon, 1990).

For a cohesive frictional column material the lower bound solution of ultimate vertical stress of RS by a group of end-bearing columns, in function of the friction angle of columns material (either φ < 19.5° or φ > 19.5°) is given by (Bouassida et al, 1995):

$$Q^{-}_{ult} / A = \sigma_{ult,rs} = (1-\eta)\sigma_{ult,s} + \eta\sigma_{ult,c} \qquad [1]$$

From Eq (1) the predicted ultimate vertical stresses induced within column material and initial soil respectively $\sigma_{ult,c}$ and $\sigma_{ult,s}$ are expressed in terms of internal friction angle and cohesion of column material C_c, φ and cohesion of initial soil C_s. Then, the allowable vertical stress of RS, denoted $\sigma_{all,rs}$ is introduced Consider the factor of safety against punching of the RS, denoted F_{rs}, the allowable bearing capacity of RS is:

$$\sigma_{all,rs} = \frac{(1-\eta)\sigma_{ult,s} + \eta\sigma_{ult,c}}{F_{rs}} \qquad [2]$$

As first approximation the lower bound estimation of the bearing capacity is associated to a factor of safety as: $1 < F_{rs} < 2$. The allowable bearing capacity of RS, compared to the mean vertical stress induced by the working load of foundation, denoted Q_{work}, should comply with the condition:

$$Q_{work} / A \leq \sigma_{all,rs} \quad [3]$$

Combining Eqs (2) and (3) the minimum IAR, denoted $\eta_{\min}$, is identified:

$$\eta \geq \frac{F_{rs}(Q_{actual} / A) - \sigma_{utl,s}}{\sigma_{utl,c} - \sigma_{utl,s}} = \eta_{\min} \quad [4]$$

The minimum IAR identified from Eq (4) corresponds to the needed quantity of column material to be incorporated in the initial soil such that the ultimate bearing capacity increases from $\sigma_{ult,s}$ to $\sigma_{ult,rs}$. Otherwise, if $\eta_{\min} \leq 0$ the reinforcement is unnecessary since the allowable vertical stress of unreinforced soil complies with the working load exerted by the foundation.

The novel methodology of design herein is extendable to the study of reinforcement by floating columns of length lower than the stratum depth H > H_c (Fig. 1) Bouassida et al (2009) have demonstrated that lower bounds of the ultimate bearing capacity of RS by end bearing columns remain valid in the case of floating columns under a restriction on the length of columns that usually occurs in practice. Therefore, the methodology of design herein can be also applied to predict the minimum IAR in case of floating columns.

4 SETTLEMENT VERIFICATION

In the framework of linear elasticity the apparent Young modulus of RS by columns, perceived as a homogenized medium, can be approximated. In particular, when carrying out the construction of statically allowable stress fields a lower bound of the apparent Young modulus of RS, E^{-}_{rs} is determined (Bouassida et al, 2003). For a rigid foundation, of area A, subjected to the allowable working load Q_{actual}, and by assuming a uniform settlement of RS δ_r we have:

$$E^{-}_{rs} \geq \frac{Q_{actual} / A}{\delta_r / H_c} \quad [5]$$

It is demonstrated that the lower bound of apparent Young modulus of RS is greater than the so called “homogenized” Young modulus expressed by: $E_{hom} = (1 - \eta) E_s + \eta E_c$. Consequently, from Ineq (5) a more conservative prediction of settlement of RS denoted δ_r, is obtained:

$$\delta_r \prec \frac{(Q_{all} / A) H_c}{(1-\eta)E_s + \eta E_c} = \delta^{+}_r \quad [6]$$

The predicted upper bound estimate of settlement δ^{+}_r from Eq (6) is associated to a maximum IAR $\eta_{\max}$. It is then required that the allowable settlement of RS, as given data $\overline{\delta_r}$, should comply with δ^{+}_r as:

$$\overline{\delta_r} \leq \delta^{+}_r \quad [7]$$

As first verification of settlement we need to check whether the minimum IAR calculated from Eq (4) complies or not with the prescribed allowable settlement of RS. If yes, that might be the case of improvement of vibro compacted loose sands, then the predicted minimum IAR $\eta_{\min}$ is agreed for the final design.

In case minimum IAR does not comply with the allowable settlement of RS, that usually happens for reinforced soft clays by stone columns, then we need to increase the IAR such that: $\eta \succ \eta_{\min}$.

The design procedure is continued by combining Ineqs (5) and (6), and then one obtains:

$$\eta \leq \frac{(Q_{all} / A)(H_c / \overline{\delta}_r) - E_s}{E_c - E_s} = \eta_{\max} \quad [8]$$

From Ineq (8) it is then identified a maximum IAR, denoted $\eta_{\max}$, beyond which the reinforcement will be definitely overestimated since both predicted stress and settlement comply with allowable values. Taking account of ineqs (4) and (8) a bounding of the IAR is obtained:

$$\eta_{\min} \leq \eta \leq \eta_{\max} \quad [9]$$

Ineqs (9) provides the targeted IAR that complies both with allowable bearing capacity and settlement of RS. Therefore, an optimized IAR η_{opt} is determined in function of the allowable settlement.

In case of floating columns, due to linear elastic assumption that is based on the principle of superposition, it is postulated that the total settlement is the sum of two components related respectively to the settlement of RS mass, i.e. δ_r, and that of the non RS under layers δ_{nr}. The settlement of RS δ_r is then estimated as detailed above for end bearing columns. In addition, it is necessary to verify that the total settlement $\delta_{tot} = \delta_r + \delta_{ur}$ is allowable as well. This verification applies when the non reinforced under layers belong to the category of compressible saturated clays in which a long term consolidation settlement is induced. The settlement estimation of unreinforced soil layers is predicted by the one dimensional Terzaghi’s theory of consolidation.

5 ILLUSTRATIVE CASE HISTORY

An oil storage tank was built at Zarzis terminal on reclaimed area at Tunisian South East Coast. The working load of the tank is approximated as quasi-uniform vertical stress of 120 kPa, which exceeds the allowable bearing capacity of initial soil. Therefore, it was aimed the increase of allowable bearing capacity at least to 120 kPa and the reduction of tank's settlement to the allowable limit of 6 cm which slightly exceeds the ratio 1/1,000 of diameter tank usually required for oil tanks projects. Reinforcement by end-bearing stone columns was agreed to make sure the overall stability of tank. The reinforcement was executed along an average depth of 7 m with a nominal diameter of columns equals at 1.2 m installed in equilateral triangular mesh. Figure 3 summarizes the geotechnical properties of initial soil and column material.

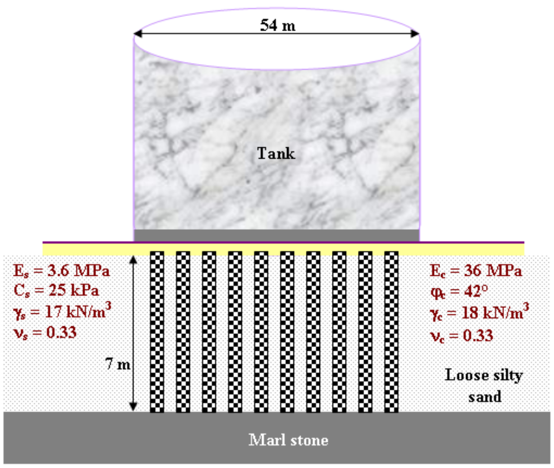


Figure 3. Tank on improved soil by stone columns

5.1 Prediction of bearing capacity

By using software "Columns 1.0" (Bouassida & Hazzar, 2011), for the Tunisian case history, it is indicated a minimum improvement area ratio η_{min} = 13 % is required. As a matter of fact, the allowable bearing capacity of unreinforced soil is approximated by:
5.7 C_s/3 = 47.5 kPa that is much less than the working load of tank of 120 kPa. Therefore, a minimum of reinforcement by stone columns equal to 13% of tank's area is needed to increase the allowable bearing capacity.

5.2 Prediction of settlement

It is assumed that the tank carrying load q= 120 kPa is uniform. For such a loading, it results, on the soil surface, an excess of vertical stress, denoted $\Delta\sigma$, which varies with the distance from the centre line of tank; we have $\Delta\sigma_{centre}$ = q, and $\Delta\sigma_{edge}$ = 0.48 q.

The settlement of reinforced soil is predicted along a small depth H compared to the tank diameter: H/2R = 7/54 = 0.13, then it is reasonable to neglect the horizontal component of displacement in the reinforced soil mass, especially at the centreline of tank. Moreover, since the reinforced soil area is greater than the tank one, the assumption of zero horizontal displacement becomes acceptable.

It has revealed η_{min} = 13 % does not comply with the allowable settlement of 6 cm. Therefore, by using "Columns 1.0" it has predicted the optimal improvement area ratio η_{opt} = 30.64 %.

The settlement predictions are summarized in Table 1 at the centre and the edge of tank.

Table 1. Settlement predictions of Tank.

Methods	Settlement at Centreline (cm)	Settlement at Edge (cm)
Recorded	--	3.0
Bouassida et al (2003)	5.8	2.8
French Standard (2005)	5.5	2.6
Balaam & Booker (1981)	5.1	2.4
Priebe (1995)	6.1	2.1

Adding to the increase of bearing capacity it is noticed that the reinforcement by stone columns has led to a significant reduction of settlement. For the majority of methods, this reduction is about five times the settlement of reinforced soil. Also, the comparison between settlement predictions for this project has shown a good agreement between methods suggested by Bouassida et al (2003), Balaam & Booker (1981) and the French recommendations (2005); despite the difference between models of reinforced soil considered by these methods all assuming the linear elastic behaviour for reinforced soil constituents of RS. In fact, the predicted settlements by these methods appear the closest to recorded data.

5.3 Adopted design

The improvement area ratio equals at 35%, the total volume of added material is 4,908 m^3. Consider a diameter column equals 1.2 m, the spacing between columns will be 1.9 m and the number equals 708. Meanwhile, the design by using Columns 1.0 software has led to η = 30.64%, the spacing between columns equals 2.06 m and the number of columns 620. Therefore, it appears that an overestimated design was decided for this project as it can be interpreted from Figure 4.

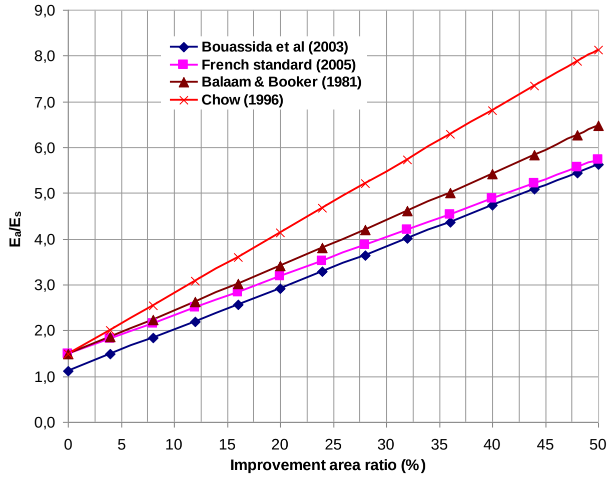


Figure 4. Normalized apparent modulus of reinforced soil versus the improvement area ratio

CONCLUSIONS

A methodology has been suggested to allow a comprehensive design of foundations (rafts, strip footings, etc) resting on reinforced soils by columns.

This methodology successively considers the bearing capacity and settlement verifications in the design procedure as regarded to previous methods of design which only focus on unique criteria, i.e. settlement or bearing capacity. The main advantages of the suggested methodology of design are; its validity for all columns techniques installation, arbitrary shaped foundations and applicability for end-bearing and floating columns.

For designers, the improvement area ratio is targeted in a given range complying with the stability of the foundation. The study of a case history has shown the efficiency of the proposed methodology in the way that an overestimated design is avoided. In addition, for practical purpose, the methodology was implemented in Columns 1.0 software which constitutes a viable tool for optimized and interactive design applicable to a variety of geotechnical structures.

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