

Novel tool for optimised design of reinforced soils by columns

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This paper describes the use of some new software (Columns 1-0) to undertake the design of foundations on soils reinforced by columns. First, the main advantages of columnar-reinforced systems are briefly reviewed: namely the increase of bearing capacity, the reduction of settlement, the acceleration of consolidation and the prevention of liquefaction potential. These advantages are usually predicted from analytical calculations and quantified after recorded field data. Second, the design methodology incorporated in this new software is described. Based on results obtained essentially by the 'group of columns' model and by the composite cell model, this methodology aims to optimise design which makes it possible to avoid overestimated quantities of column material under rigid or flexible foundation. Different types of reinforcement by columns such as the most frequently used stone columns, sand-compacted columns, deep mixing soil method, etc. can be simulated by this new software. A worked example is presented to illustrate the design provided by the software: input data, loading configurations, geotechnical profile and the drawing of designed solutions.

Notation

A_c	total cross-section of the columns
A_s	area of unreinforced soil
C_s	undrained cohesion of initial soil
E_c, v_c	linear elastic characteristics of material columns
E_s, v_s	linear elastic characteristics of initial soil
F	global safety factor
H_c	column length
q	assumed uniformly applied load
q_{ult}	ultimate bearing capacity (limit state analysis)
q_{all}	allowable bearing capacity of reinforced soil
s	settlement prediction
γ_c	total unit weight of initial soil (resp. column material)
γ_s	total unit weight of initial soil
η_{min}	minimum required reinforcement complying with allowable bearing capacity
η_{max}	corresponds to the maximum reinforcement complying with allowable settlement
η_{opt}	optimal improvement area ratio
$\Delta\sigma$	excess of vertical stress
φ_c	friction angle of column material

1. Introduction

Columnar reinforcement is one of the techniques used for the improvement of both the physical and mechanical characteristics of weak and often very compressible soils. The design of foundations on reinforced soil using columns is related to the verification of both bearing capacity and settlement. Previous contributions to the literature have focused either on the bearing capacity aspect, or on the settlement aspect (Balaam and Booker, 1981); this latter being the most often seen in practice. Most of the suggested methods applied to restricted types of column installa-

tion such as stone columns by Barksdale and Bachus (1983), Priebe (1995) and Normes Françaises (2005), or for cement (cement–lime) columns by Broms (1982, 2000) and Terashi and Tanaka (1981). In an early study Barksdale and Bachus (1983) investigated the bearing capacity and settlement of foundations on purely cohesive weak soil that had been reinforced by end-bearing purely frictional columns. The bearing capacity is expressed in terms of the mean characteristics of the reinforced soil, whereas the settlement is predicted by assuming an elastoplastic behaviour which is incorporated in the composite cell model.

Currently there is a limited number of numerical tools for the design of foundations on reinforced soils by columns. Indeed, the review of references on this subject has shown four available products: namely DC-vibro, Colany, Greta and Stonec. None of these products offers the opportunity to investigate the connection between bearing capacity and settlement, regardless of the mechanical model of reinforced soil. Furthermore, these existing tools do not permit a comparison between two or more options related to the installation techniques, for example, stone column, deep mixing, controlled column modulus, etc. Therefore the development of some new software (Columns 1-0) was suggested and development started in 2005 at 'Pépinière des Entreprises et des Projets', Manartech, Tunisia, to provide an efficient and unified design tool in which several options are available.

The first version of this software considers the configuration of the reinforcement as depicted in Figure 1 which illustrates the reinforced soil subjected to a loaded foundation on three-dimensional (3D) column-reinforced soil. All columnar reinforcement techniques (stone columns, sand-compacted columns, deep mixing, etc.) can be simulated by this new software.

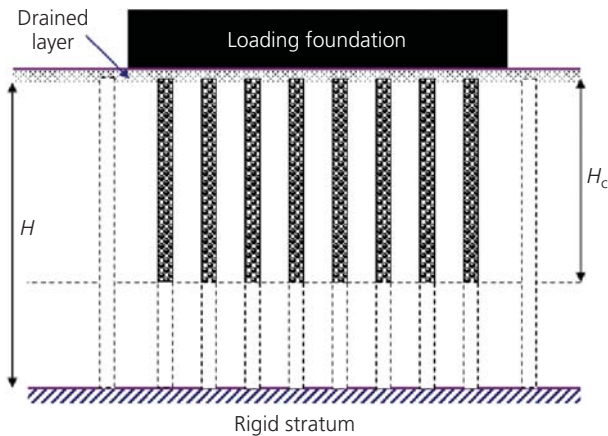


Figure 1. Columnar reinforced soil model

The prediction of the ultimate bearing capacity of reinforced soil is carried out on the basis of lower bounds calculated by the direct approach of limit state design (Bouassida *et al.*, 1995), whereas the settlement prediction is based on results derived from the method suggested by Bouassida *et al.* (2003) in linear elasticity. Furthermore, based on a 'poro-elastic' model, the new software enables the prediction of the evolution of consolidation settlement as a result of the loading history (i.e. staged construction) in the case of soft soil improved by drained column material (Guetif and Bouassida, 2005).

The first part of this paper considers the characteristics of columnar-reinforced soils and the performance of improved soils. Second, the methodology of design of columnar-reinforced systems is explained by focusing on approaches and methods of bearing capacity and settlement predictions incorporated in this new software. Finally, a case history is examined in order to assess the predictions provided by the use of this software and to highlight its usefulness in view of the optimised reinforcement. A comparison between different methods of design is then presented and illustrated.

2. Reinforcement by columns

Sometimes the characteristics of a soil are not suitable for shallow foundations, because of the lack of bearing capacity and very often because of pronounced settlement. According to experience from many projects, reinforcement by columns can generally be applied to two types of soil.

- (a) Soft clays characterised by a moderate to very low undrained shear strength (lower than 30 kPa) and a Young's modulus which is often lower than 2.5 MPa.
- (b) Loose sands, particularly when saturated. The relative density of such non-cohesive soils is less than 50% or equivalently their shearing resistance is 29° and their Young's modulus varies from 8 to 15 MPa, (Bergado *et al.*, 1996).

The most recent situation for reinforcement by columns (Figure

1) is carried out in the form of vertical inclusions (with assumed circular cross-sections) made up of added material that has much better mechanical characteristics than those of the initial soil. Depending on the type of initial soil and its grain size distribution, the column can consist of either of the two material types described below.

- (a) Coarse and drained materials having an angle of friction greater than 38° (with cohesion mostly neglected) are used either in 'stone columns' or in the 'sand compaction piles' techniques. Baumann and Bauer (1974) have previously reported that loose or medium dense sands can be vibro-compacted with slender, cylindrical vibrators. Cohesive or organic soil can be improved by the vibro-replacement method using selected granular material which is vibrated into the initial soil.
- (b) In situ soft soil can be treated by adding a percentage of binder (lime, cement or a mixture of the two) of about 8 to 12% of the mass of the soil that is to be improved. This situation rather corresponds to the 'deep mixing method' (Bergado *et al.*, 1996; Bouassida and Porbaha, 2004; Broms, 2000).

Current projects involving the column reinforcement technique are those in which uniformly loaded foundations have been used, such as warehouses, industrial and commercial buildings, silos and tanks, etc. In particular, stone columns significantly reinforce soft ground; they make very efficient use of the soil near the surface and are ideal for light loads. They are, however, less effective at supporting heavy loads because they cannot transfer the applied stresses to the deeper layers of the soil (Hughes and Withers, 1974).

Reinforcement by columns may provide a very competitive alternative in comparison with pile foundations which are not usually cost effective and require a longer duration of installation. Reinforcement by columns is applied for a large variety of loaded foundations, for example rafts or shallow footings, high embankments, etc.

The following advantages are provided by columnar reinforcement.

- (a) An increase of bearing capacity that results from higher strength characteristics of column composite material.
- (b) The reduction of settlement which results from higher stiffness of column material.
- (c) The acceleration of primary consolidation when the constitutive column material has a high permeability simulates the role of vertical drains which contribute in accelerating the soft soil consolidation (Guetif and Bouassida, 2005).

These advantages have been assessed for different types of column installation either from in situ tests (Bergado and Lam, 1987) or from laboratory tests and scaled model results (Bouassida, 1996; Bouassida and Porbaha, 2004).

The significant reduction of liquefaction is another advantage that can be achieved by using the vibro compaction technique in the case of saturated loose sand in an area with potential seismic risk (El Ouni *et al.*, 2009).

In addition to the advantages listed above, columnar reinforcement may contribute to the improvement of the initial soil. Indeed, the installation of a vibrated stone column by lateral expansion induces the improvement of mechanical characteristics associated with the primary consolidation phenomena in soft clay. Such an improvement of initial soil characteristics is usually evidenced by in situ test results performed before and after the installation of the stone columns (Alamgir and Zaher, 2001). By performing a numerical simulation of stone column installation, Guetif *et al.* (2007) quantified the rate of Young's modulus improvement and its extent in soft clay.

3. Design background

3.1 Design characteristics

Bouassida (2001) has introduced a novel methodology for the design of foundations built on columnar reinforced soils which essentially consists of estimating an optimised improvement area ratio. This latter complies with bearing capacity and settlement verifications.

The improvement area ratio denoted by η is the ratio of total cross-section of a group of columns to the total area of loaded foundation under which the group of columns is located (Figure 2). Therefore the reinforcement of soil outside the area of foundation, if applied, is not taken into account.

The total area, denoted A , of contact between the foundation and the reinforced soil is defined as

$$A = A_c + A_s$$

where $A_c = \eta A$ is the total cross-section of the columns and $A_s = (1 - \eta)A$ is the area of unreinforced soil.

Thus, the improvement area ratio is

$$1. \quad \eta = \frac{A_c}{A}$$

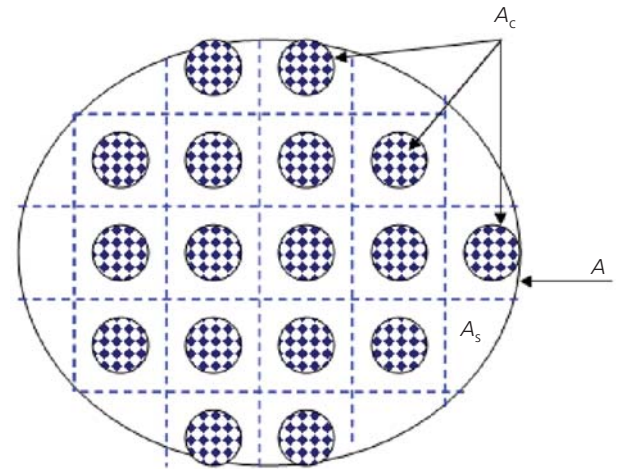


Figure 2. View plane of foundation resting on columnar reinforced soil

Table 1 shows the current techniques of reinforcement using columns, the appropriate type of initial soil and values of the improvement area ratio obtained in practice.

As shown in Figure 2 the shape of the foundation area is arbitrary and the arrangement of columns need not necessarily be in a regular pattern, as is the case in current practice. Moreover the reinforcement can be designed for floating columns (Figure 1) for which the bearing capacity calculation has been investigated by Bouassida *et al.*, 2009b; from their study a maximum length of columns was derived after performing a calculation of the lower bound of the bearing capacity and taking gravity into account.

3.2 Bearing capacity of columnar-reinforced soil

The prediction of ultimate bearing capacity of columnar-reinforced soil started earlier with the use of the 'isolated column' model (Normes Françaises, 2005). Such a simple model only considered the applied load on the column head, and the value of improvement area ratio was disregarded. Later the bearing capacity was also examined by using the composite cell model: a cylindrical column of radius a , surrounded by a volume of soil, with external equivalent radius b (Figure 3). This latter depends on the pattern of columns and their spacing. Using the composite cell model, the improvement area ratio, after Equation 1 gives

Initial soil (to be reinforced)	Column material	Improvement area ratio
Soft clays	Sand piles	$5\% < \eta < 15\%$
Stone columns	Silty clays	$15\% < \eta < 33\%$
Lime-cement treated soil	Highly compressible soft clays	$20\% < \eta < 70\%$

Table 1. Practical values of improvement area ratio

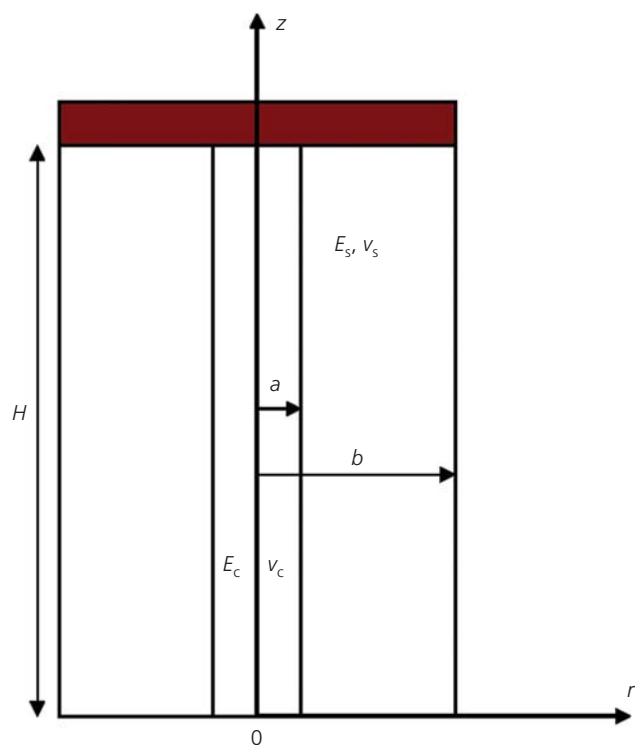


Figure 3. Composite cell model

$$2. \quad \eta = \frac{a^2}{b^2}$$

As commonly assumed, the horizontal displacement is zero at the external boundary, $r = b$, and zero displacement at the bottom side, $z = 0$, which complies with end-bearing column type.

Based on the ‘composite cell’ model, several suggestions have been proposed for prediction of the bearing capacity of reinforced soils (Barksdale and Bachus, 1983; Baumann and Bauer, 1974), and for the study of its behaviour (Balaam and Booker, 1985; Poorooshasb and Meyerhof, 1997).

Since 1990, the bearing capacity of foundations on soil reinforced by columns has been investigated by performing direct ap-

proaches using limit-state analysis which made it possible to obtain comprehensive results for reinforcement cases by the ‘trench’ model (Bouassida and Hadhri, 1995), the ‘composite cell’ model (Bouassida, 1996), and the ‘group of columns’ model (Bouassida *et al.*, 1995). These results are applicable to any columnar installation techniques (stone columns, deep mixing, sand columns, etc).

For the verification of bearing capacity, the global safety factor of foundation is introduced. This is defined by

$$3. \quad F = \frac{q_{ult}}{q_{all}}$$

where q_{ult} and q_{all} are the ultimate bearing capacity (limit state analysis) and the allowable bearing capacity of reinforced soil, respectively.

Table 2 presents the design methods for predicting the ultimate bearing capacity incorporated in the new software (Columns 1-0) depending on the type of constitutive column material. As can be seen, the limit state analysis results can be utilised for any type of column material (or installation method) whereas other methods can only be considered for a given type of column installation method. Furthermore, it should be mentioned that none of the existing methods of design have taken into account the improvement of ambient soil characteristics due to column installation. The safety factor introduced in Equation 3 is equal to one when considering the limit state analysis approach due to its conservative predictions (Jellali *et al.*, 2007) and because a minimum value is intended.

3.3 Settlement prediction of reinforced soil

The prediction of settlement logically follows the calculation of allowable bearing capacity of reinforced soil. Indeed, for foundations resting on compressible soils, the magnitude of settlement and its evolution in time both require special attention as they are usually used for studying the stability of the foundation. Thus, recourse to reinforcement by columns represents one of the most adequate solutions to reduce the settlement of layers located in practice at a depth at which 70 to 90% of settlement of reinforced soil occurs.

Method of prediction	Installation techniques	Safety factor
Limit analysis approach (lower bound)	All	= 1
Normes Françaises (2005)	Stone columns	= 2
Broms (1982)	Deep mixing	> 1
Terashi and Tanaka (1981)	Deep mixing (cement)	> 1

Table 2. Design methods for predicting bearing capacity

In order to predict the settlement of columnar reinforced soil, various methods have been proposed, the majority of which consider the linear elastic behaviour for both initial soil (to reinforce) and for the constitutive material of the columns. Balaam and Booker (1981) considered the ‘composite cell’ model and derived an analytical solution for linear elastic settlement predictions. This model has also been studied by many others in different ways: the semi-empirical method (Porooshab and Meyerhof, 1997; Priebe, 1995), the homogenisation method in linear elasticity (Ben Saïd *et al.*, 2004) and the elastoplastic behaviour method (Abdelkrim and de Buhon, 2007). From the practical view point, the French recommendations (Normes Françaises, 2005) were published to provide settlement predictions based on the ‘composite cell’ model for which oedometric conditions are integrated.

Indeed, based on the ‘group of columns’ model, the settlement prediction s in linear elasticity is determined as a function of a lower bound of apparent Young modulus of reinforced ground E_a , which is generally expressed as (Bouassida *et al.*, 2003)

$$4. \quad E_a \frac{qH_c}{s}$$

where q is the assumed uniformly applied load and H_c is the column length. By this method an upper bound estimation of settlement is predicted.

Essentially, the E_a modulus depends on the improvement area ratio η and the linear elastic characteristics of initial soil E_s , ν_s and material columns E_c and ν_c . The linear elastic variational method provides design charts for the cases of circular and rectangular foundations resting either in regular or in arbitrary column patterns as a result of considering the ‘group of columns’ model (Bouassida *et al.*, 2003).

The methods incorporated in the new software for predicting settlement of reinforced soil are summarised in Table 3 depending on constitutive column material and the model of reinforced soil. It should be noticed that the well known Priebe’s method is not included. Recently Ellouze *et al.* (2010) showed that the use of Priebe’s method, restricted to the stone columns technique, for settlement estimation is debatable since three options can be considered (settlement reduction factors n_0 , n_1 and n_2) from which three different predictions are made. Therefore in the new

software (Columns 1.0) only simple and rational methods based on linear elastic behaviour were incorporated.

When columns are made up of drained constitutive material they are more likely to behave identically to vertical drains when the reinforcement of soft clays is in question. Therefore acceleration of the consolidation should also be considered. In order to predict the evolution of settlement against time, therefore, the poroelastic approach (Guétif and Bouassida, 2005) is programmed in the new software. The evolution of the settlement of columnar-reinforced soil is predicted for a given staged loading.

4. Columns 1.0 software

This tool considers the design of foundations on columnar reinforced soil (for all installation techniques) by essentially analysing the verifications of bearing capacity, settlement and acceleration of consolidation (Bouassida *et al.*, 2009a).

The design is carried out by adopting a novel methodology which analyses, either separately or in connection, the predictions of bearing capacity and settlement (Bouassida, 2001). In this manner, the design procedure provides an optimised value of improvement area ratio which influences the cost of reinforcement by columns. Therefore, the optimised improvement area ratio is bounded as

$$5. \quad \eta_{\min} \leq \eta_{\text{opt}} \leq \eta_{\max}$$

where η_{\min} represents the minimum required reinforcement complying with allowable bearing capacity and η_{\max} corresponds to the maximum reinforcement which complies with allowable settlement. The design steps provided by the new software are illustrated in Figure 4. This paper focuses on the determination of the optimised improvement area ratio that is the key parameter for the cost of reinforcement. Multi-layered soil profiles can be treated, to a maximum of seven layers, for end bearing and floating column reinforcements.

4.1 Determination of minimum improvement area ratio (η_{\min})

According to the verification of bearing capacity, the prediction of minimum improvement area ratio represents the first step of the methodology programmed in Columns software. The η_{\min} value is estimated after predictions of allowable bearing capacity, which are deduced from lower bound solutions of limit state analysis

Method of prediction	Installation techniques	Model
Bouassida <i>et al.</i> (2003)	All	Group of columns
Normes Françaises (2005)	Stone columns	Unit cell model
Balaam and Booker (1981)	All	Unit cell model
Chow (1996)	All	One dimensional

Table 3. Design methods for predicting settlement

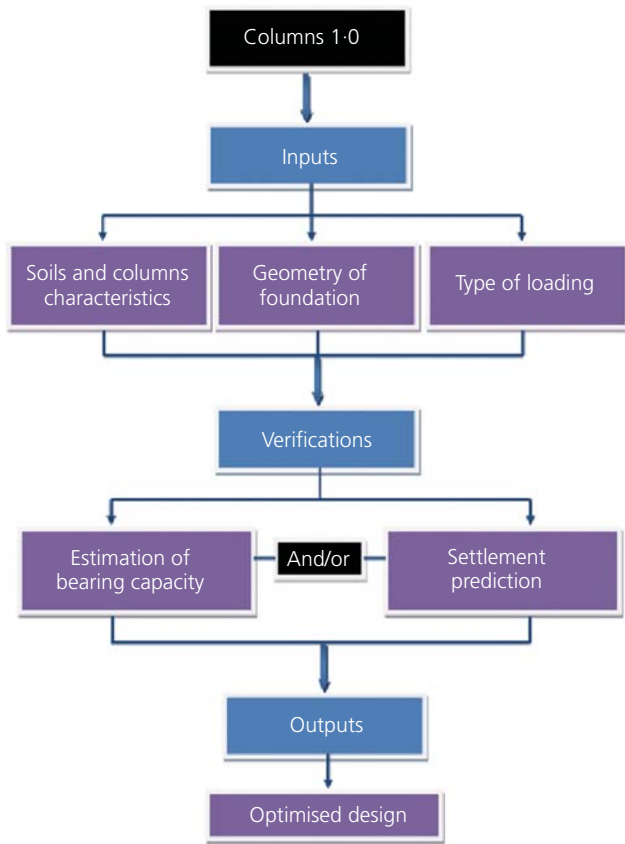


Figure 4. Operating diagram of Columns 1-0 software

approaches. For this method two cases are considered: gravity of reinforced soil constituents is either taken into account or not. Indeed, it has been shown that as different unit weights of initial soil and column material are considered, the lower bound of bearing capacity is sensitively influenced (Bouassida *et al.*, 2009b).

To determine the value of η_{\min} the required data are the load applied by the foundation, and the characteristics of the initial soil and column material (the thickness of the layer, column length, cohesion, friction angle and unit weight).

4.2 Estimation of the optimal improvement area ratio (η_{opt})

As the main objective, Columns 1-0 software enables the prediction of the optimal improvement area ratio η_{opt} as referred to the

criteria of allowable settlement. This criteria is required data when Columns 1-0 software is used. Two options are programmed for the calculation of η_{opt} value depending on the geometry of foundation. For all installation techniques when a rectangular or circular foundation is to be designed, the Bouassida *et al.* (2003) method is used to predict η_{opt} . For other foundation geometries, η_{opt} is determined by the French standard in the case of reinforcement by stone columns, and by Balaam and Booker's method in the case of the deep mixing technique. Note that for all types of foundation geometry the Young's moduli and the Poisson's ratios of the initial soil and column material are required data (Bouassida and Hazzar, 2009).

4.3 Characteristics of design

Once the type of column pattern has been chosen (i.e. rectangular, triangular, hexagonal or unspecified) other data are needed for the design, namely the column diameter, spacing between columns and total number of columns. Table 4 presents the output results after optimising the improvement area ratio for the case of end-bearing stone column reinforcement.

4.4 Outputs and illustrations

The new software presented here enables the prediction of settlements prior to and after reinforcement; the bearing capacity of reinforced soil; the evolution of consolidation settlement against time; drawings of reinforced soil and several outputs of the designed foundation. The detailed descriptions of possibilities offered by this new software are given in Bouassida and Hazzar (2009). As an example, Figure 5 illustrates the variation of normalised apparent modulus of reinforced soil as a function of the improvement area ratio by several methods of settlement predictions. Predicted results derived using this new software have been assessed through analysis of three case histories detailed by Ellouze *et al.* (2010).

5. Case history: oil storage tank at Zarzis, Tunisia

An oil storage tank was built at Zarzis terminal on a reclaimed area on the Tunisian south-east coast. The load applied by the tank was approximated as a quasi-uniform vertical stress of 120 kPa, which exceeded the allowable bearing capacity of the initial soil. Therefore, it was aimed to increase the allowable bearing capacity to at least 120 kPa and to reduce the tank's settlement to the allowable limit of 6 cm which slightly exceeded the ratio 1/1000 of the tank diameter which is usually required

η_{\min} :%	η_{opt} :%	η_{\max} :%	Column diameter: m	Spacing between columns: m	Total number of columns	Pattern	Volume of column material: m ³
13-13	30-64	43-2	1-2	2-06	620	Triangular	4908-42
13-13	30-64	43-2	1-2	1-68	620	Hexagonal	4908-42
13-13	30-64	43-2	1-2	1-91	620	Squared	4908-42

Table 4. Output results generated by new software

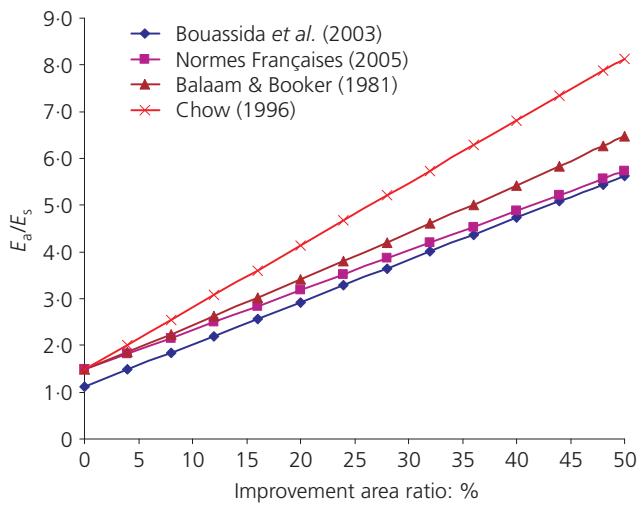


Figure 5. Normalised apparent modulus of reinforced soil plotted against improvement area ratio by Columns 1-0 software

for oil tank projects. Reinforcement by end-bearing stone columns was agreed to ensure the overall stability of the tank. The reinforcement was installed along an average depth of 7 m with a nominal column diameter of 1.2 m, installed in an equilateral triangular mesh. Figure 6 summarises the geotechnical

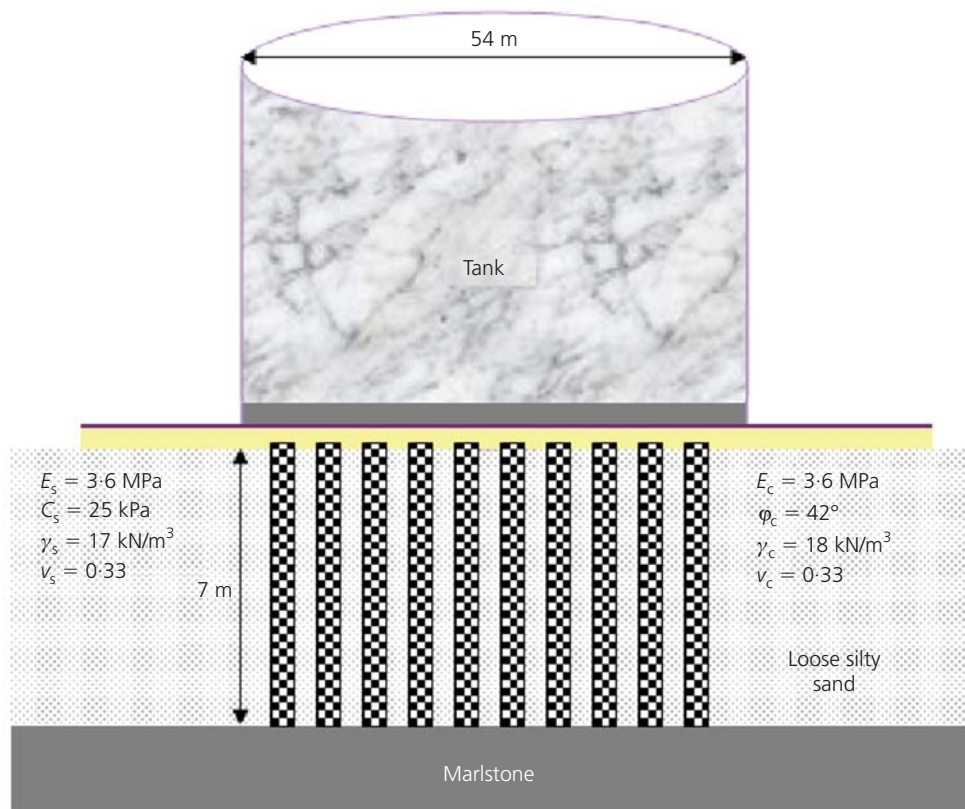


Figure 6. Tank resting on silt sand improved by stone columns

properties of the initial soil and column material and shows stone columns installed in a circular area of radius equal to the tank radius.

5.1 Predictions of bearing capacity

Using the new software for this case history, the results indicated that a minimum improvement area ratio $\eta_{\min} = 13\%$ was required. In fact, the allowable bearing capacity of unreinforced soil was approximated by $5.7C_s/3 = 47.5$ kPa which was much less than the working load of the tank, which was 120 kPa. Therefore, a minimum reinforcement by stone columns over 13% of the area of the tank was needed to increase the bearing capacity.

As reinforcement of stone columns is in question, a comparison between the allowable bearing capacity predictions (q_{all}) derived as the lower bound of limit state analysis (LSA) and the values obtained using the French recommendations (Normes Françaises, 2005) was performed (Table 5).

It can be seen that the French recommendations which employ the isolated column model, greatly overestimated the allowable bearing capacity of the reinforced soil with a factor of safety of 2. The French recommendations do not take the improvement area ratio into account and this leads to the overestimated prediction of allowable bearing capacity.

Method of prediction	Factor of safety	q_{all} : kPa
LSA (gravity taken into account)	1	120
LSA (gravity not taken into account)	1	128.5
Normes Françaises (2005)	2	347

Table 5. Predicted allowable bearing capacity for $\eta_{min} = 13\%$

5.2 Predictions of settlement

It was assumed that the tank carrying load $q = 120$ kPa was uniform. This loading results in an excess of vertical stress on the soil surface, denoted by $\Delta\sigma$, which varies with the distance from the centre line of the tank. Here $\Delta\sigma_{centre} = q$, and $\Delta\sigma_{edge} = 0.48q$.

As the settlement of reinforced soil is predicted along a small depth H in comparison with the tank diameter: $H/2R = 7/54 = 0.13$, it is reasonable to neglect the horizontal component of displacement in the reinforced soil mass, especially at the centre line of the tank. Moreover, as the reinforced soil area is assumed equal to the the tank area, the assumption of zero horizontal displacement becomes acceptable.

In the design methodology incorporated in the new software, the settlement of reinforced soil is first estimated for the minimum value of improvement area ratio previously predicted after bearing capacity verification. This revealed that $\eta_{min} = 13\%$ did not comply with an allowable settlement of 6 cm. However, using the new software an optimal improvement area ratio $\eta_{opt} = 30.64\%$ was predicted.

The settlement predictions are summarised in Table 6 for both the centre and the edge of the tank.

It should be noted that in addition to the increase of bearing capacity, reinforcement by stone columns led to a significant reduction of settlement. For the majority of methods, this reduction was about five times the settlement of the reinforced soil. Furthermore, comparison between settlement predictions for this project has shown a good agreement between methods suggested by Bouassida *et al.* (2003), Balaam and Booker (1981)

and the French recommendations (Normes Françaises, 2005) despite the differences between the reinforced soil models utilised by these methods, all of which assume linear elastic behaviour for reinforced soil constituents. In fact, the predicted settlements by these methods appear the closest to recorded ones.

5.3 Adopted design

According to the new software introduced here, the improvement area ratio was estimated as $\eta = 30.64\%$; the verifications of allowable bearing capacity and settlement of columnar-reinforced soil were set without taking account of the improvement of the initial soil characteristics and reinforcement around the tank area. For $\eta = 30.64\%$, the spacing between columns was evaluated as 2.06 m and the number of columns 620.

The design for the tank project was executed in 1990 with an improvement area ratio equal to 35% and the total volume of added material is 4908 m³. For a column with diameter 1.2 m, the spacing between columns will be 1.9 m and the number is 708. Therefore, it appears that an overestimated design was produced for this project. Thus, this case history illustrates the usefulness of studying the bearing capacity and settlement verification which is one of the affordable options provided by this new software.

Finally the new software constitutes a simple tool that provides an initial design that targets the optimisation of the improvement area ratio which, as key factor, controls the cost of treatment. However, the study of behaviour of columnar-reinforced foundations cannot be investigated using the new software and so this task is addressed by numerical codes (such as those based on the

Method of prediction	Settlement at centre line of tank: cm	Settlement at edge of tank: cm
Recorded	–	3.0
Bouassida <i>et al.</i> (2003)	5.8	2.8
Normes Françaises (2005)	5.5	2.6
Balaam and Booker (1981)	5.1	2.4
Priebe (with η_2)	6.1	2.1

Table 6. Settlement predictions by methods incorporated in new software and Priebe's method

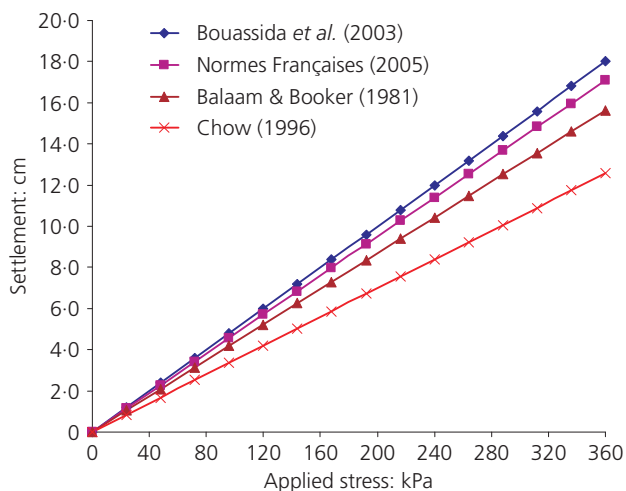


Figure 7. Settlement predictions by Columns 1.0 software for Tunisian case history (working load = 120 kPa)

finite element method) once the optimised improvement area ratio is fixed.

6. Conclusions

The principles of the design of foundations on soil reinforced by columns were investigated in the present study, namely the installation techniques, initial soil, column material and actual improvement area ratio.

Only limited tools exist to address the design of columnar-reinforced systems and this led to the development of some new software (Columns 1.0) which has been presented here.

In its first version, the new software investigates the configuration of the load applied by a rigid or flexible foundation of arbitrary form on soil reinforced by a group of columns, located under the foundation and either of end-bearing or floating type. The new software includes several design options that are based on bearing capacity and/or settlement of reinforced soil in cases in which the columns are made up of drained material or not.

This new software has been shown to be a useful tool through detailed analysis of a case history in which stone columns were used as reinforcement. The design methodology incorporated in this new software makes it possible to evaluate an optimised reinforcement for comparison with the actual design.

In comparison with the existing tools, the new software presents advantages of regarding the improvement area ratio as the key parameter to be predicted, as it controls the cost of the reinforcement operation.

The results afforded by the new software should serve as convenient data to analyse the behaviour of columnar-reinforced foundations by means of numerical codes.

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