Behavior of Foundation on End-bearing Stone Columns Group Reinforced Soil

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ABSTRACT: The prediction of the settlement of foundations on soil reinforced by a group of end-bearing stone columns was investigated. 3D numerical models with constant improvement area ratio are considered into two configurations. The first configuration consists of stone columns group located in regular triangular pattern. Whilst, an equivalent reinforcement by concentric crowns is used by the second configuration. Geotechnical parameters of the reinforced soil modeled by the Mohr Coulomb constitutive law are adopted from Tunisian case history. Numerical predictions of the settlement by the finite difference code FLAC 3D and analytical ones by Columns and COLANY software are compared. It has been verified that the settlement prediction by the unit cell model is underestimated in regard to predictions obtained by the 3D reinforced soil models. Elsewhere settlement predictions by the equivalent concentric crowns are close to those obtained by the corresponding models of stone columns group reinforcement. When the equivalent concentric crowns reinforcement is adopted the increase in contact area with the soft soil does not affect the settlement prediction when total adhesion is assumed along those interfaces. Using the FLAC 3D code, it is more suitable to handle the input data by the equivalent concentric crowns to perform the computations.

KEYWORDS: Soft soils, Stone columns, Settlement prediction, Finite difference, Improvement area ratio

1. INTRODUCTION

The need for construction over soft soils remains a big challenge in geotechnical engineering. Several ground improvement techniques have been developed to make possible the construction of big variety of structures and infrastructure on soft soils with suitable stability conditions. Among those techniques, the reinforcement using stone columns knew a great development the last decades. It is well agreed that the improvement of soft soil by stone columns increases the bearing capacity of foundations built on weak soils, decreases the differential and absolute settlements, accelerates their primary consolidation and prevents liquefaction risk (McCabe et al., 2009, Bensalem et al., 2016).

The study of behavior of foundations on soil reinforced by columns relies, first, on the verification of bearing capacity and, second, on the settlement predictions (Bouassida & Carter, 2014).

From the eighties, numerous contributions were proposed to predict the settlement of foundations on soil reinforced by stone columns. Different modeling and various constitutive laws were adopted for constituents of reinforced soil (Balaam and Booker, 1981; Barksdale and Bachus, 1983; Schweiger and Pande, 1986, Abdelkrim et al., 2007, etc…).

Several authors adopted the unit cell model (UCM) for the predictions of bearing capacity and settlement of column-reinforced foundations (Balaam & Booker, 1981; Bachus and Barksdale, 1983, Bouassida, 1996, Weber et al. 2008, Black et al. 2011; Sexton et al., 2016 etc). Despite the intensive practice of the UCM, considered by several authors, since the last decade a big interest was accorded to perform numerical modeling of reinforced soil. Compared to empirical and simple analytical methods for settlement predictions, the numerical and analytical methods offer substantial advantage to oversee the behavior of foundations on soil reinforced by end-bearing stone columns by taking into account the consolidation of compressible layers Han and Ye (2001); Guetif and Bouassida (2005), Sexton and McCabe (2013). Indeed, the stone columns made up of drained material behave like vertical drains for accelerating the settlement of reinforced soil.

When the reinforcement by floating columns is intended the prediction and the evolution of the settlement of unreinforced compressible layers should be addressed carefully (Sexton et al., 2016) by taking account of secondary compression (Bryan and Sexton, 2017)

The use of a numerical code (e.g. finite difference or finite element) for the analysis of the behavior of a foundation on soil reinforced by a group of columns modeled as 3D medium is becoming much more investigated in the literature. In this regard it is noted the contributions ofBalasingam and Sathishbalamurugan (2006) and Chen et al. (2009) who investigated the behavior of column-reinforced foundations by sand columns and single aggregate pier using the FLAC 3D code.

Bouassida et al. (2017) validated the settlement predictions by Columns 1.01 software with numerical results performed by Plaxis V9.2 and FLAC 3D codes for the predictions of the behavior of soils reinforced by sand and stone columns. These numerical results also highlighted the role of stone columns in reducing both absolute and differential settlements.

This paper deals with the numerical study of the behavior of a foundation on soil reinforced by a group of end-bearing stone columns with focus on settlement reduction. The group of stone columns has been reduced to equivalent concentric crowns by adopting a full 3D model using the finite difference FLAC 3D code.

First, the classical unit cell model (UCM), which comprises an elementary volume of soil reinforced by a single stone column, is investigated to calibrate the measured settlement from data of a Tunisian stone columns case history (Solétanche-Bachy, 1990).

Second, on the basis of the calibrated UCM and related geotechnical soil parameters, three configurations of 3D models of soil reinforced by a group of stone columns are analyzed.

For the models of soil reinforced by stone columns, the improvement area ratio (IAR)is kept constant. IAR is defined as the ratio between the total cross section of reinforcing columns to the area of the loaded foundation (all columns are located under the area of loaded foundation).In turn the area of the square rigid foundation subjected to a vertical load is increased when the number of reinforcing columns increases as well. Accordingly, the breadth of numerical models is increased so that the boundary conditions on its lateral border do not affect the settlement predictions. Therefore, different reinforcement configurations by a group of stone columns arranged in a triangular pattern are considered.

Numerical predictions by the FLAC3D code are compared with results obtained by existing software. The interpretation and validity of proposed results are discussed.

2. NUMERICAL MODELING OF THE REINFORCED SOIL

The study of the behavior of foundations on soil reinforced by a group of columns is carried out using three parameters i.e. the improvement area ratio of a group of stone columns, the settlement reduction factor and the stress concentration factor defined by Eqs (1), (2) and (3), respectively:

$$\eta = \frac{A_{rein}}{A_F} \quad (1)$$

$$\beta = \frac{S_{unrein}(q)}{S_{rein}(q)} \quad (2)$$

$$n = \frac{\sigma_c}{\sigma_s} \quad (3)$$

denotes the total cross section of reinforcing columns A_{rein}located under the loaded foundation of area A_F.

$S_{unrein}(q)$and $S_{rein}(q)$ denote the settlement of unreinforced soil and reinforced soil respectively, predicted under the same allowable vertical load q.

The study of the behavior of reinforced soil can also be associated with the effect of stone columns installation, which often leads to increased stiffness and strength properties of soft soil (Ellouze et al., 2016). In this paper the settlement is predicted without taking account of such an improvement. Such recommendation is currently adopted in practicing to be on the safe side for the design.

The design of foundation on soils reinforced by columns relies on two essential verifications (Bouassida and Carter, 2014):

1st Bearing capacity: to check if the admissible bearing capacity of the foundation on the reinforced soil complies with the applied load.

2nd Settlement: to check whether the predicted settlement of the reinforced soil subjected to the applied load satisfies the allowable settlement criterion.

On the basis of those two verifications an optimized improvement area ratio is derived using the Columns 1.01 software (Bouassida and Hazzar 2012). The study of the behavior of a foundation on reinforced soil by columns is then tributary to this optimized improvement area ratio.

A three-dimensional explicit finite-difference method, incorporated in the Fast Lagrangian Analysis of Continua (FLAC) code is performed to run the numerical computations. FLAC 3D code is used for the study of the behavior of three-dimensional structures built of soils and rocks and other materials (Itasca Consulting Group, 2002). The stone column and surrounding initial soil are modeled by the elastoplastic Mohr Coulomb constitutive law. This elastic perfectly plastic model is often considered to simply describe the behavior of granular soils (sands), cohesive soils (clay and silt soils) and rocks. However, there are several constitutive laws to model soils in regard to specific behavior: hardening, softening and creep. Total adhesion is assumed between the weak soil and reinforcing stone columns.

Each group of columns is reduced to an equivalent concentric stone crowns to facilitate the implementation of 3D numerical computations using the FLAC 3D code. The models by a group of stone columns and equivalent stone crowns are compared on the basis of the predicted load-settlement curves. The results given by those numerical models by adopting the linear elastic behavior apply for the short-term condition that should be checked at the first stage. The long-term behavior of soil reinforced by stone columns involves the consolidation option with consideration of appropriate conditions that are not here considered (Castro &Sagaseta, 2009; Fessi-Guetif, 2005).

2.1 Unit Cell Model (UCM)

The UCM comprises a single stone column surrounded by soft soil with external diameter De that depends on the pattern of installed group of columns (Balaam & Booker, 1981).

The UCM assumes the following oedometer conditions:

- The horizontal displacement equals zero at the vertical border of the UCM.
- Horizontal and vertical displacements are zero at the bottom side of UCM.
- Uniform applied load q is applied at the upper side of UCM.

Assuming the linear elastic behavior for materials of reinforced soil, Balaam (2012) performed the COLANY program to compute the load-settlement response of a rigid foundation supported by a layer of clay stabilized with stone columns.

The COLANY software was developed by the centre for geotechnical research at the University of Sydney, Australia (Balaam N. P. 2012). This program is based on the analytic solution for settlement prediction of a soft clay layer reinforced by a large group of stone columns developed by Balaam and Booker (1981, 1985). The calculations computed by this program are conducted by assuming no yield in the clay or the column. The solution is computed for the settlement response of the stabilized clay when the column is fully plastic. In these analyses of the behavior of a clay layer stabilized by a large group of stone columns the well known unit cell model UCM is considered. This assumption is checked then in the COLANY software by performing elasto-plastic finite element analyses.

The UCM sketched in Figure 1, as built by the FLAC 3D code, comprises 672 finite difference zones and 735 grid-points at cycle 6609.

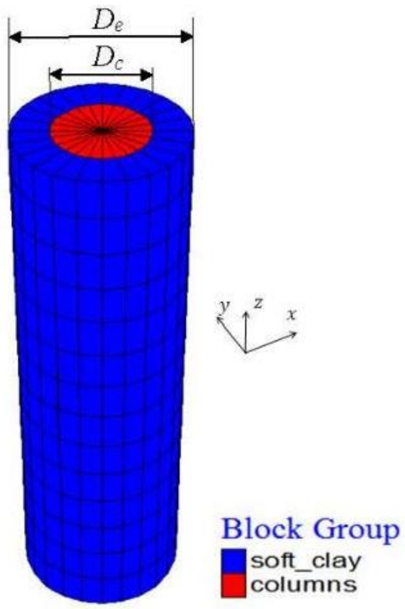

Figure 1 FLAC 3D mesh of the unit cell model

The improvement area ratio of the unit cell idealization UCM writes (Bouassida, 2016):

$$\eta = \frac{D_c^2}{D_e^2} \quad 4)$$

D_c = Stone column diameter.
D_e = External diameter of the UCM.

The characteristics of the native soil and the constitutive column material are taken from Tunisian case history of end-bearing stone columns project at Zarzis terminal (Bouassida &Hazzar, 2012). Geotechnical parameters of reinforced soil were considered from Solétanche-Bachy (1980) and Gambin(1992). Those parameters were compiled for the assessment of executed reinforcement as presented in Solétanche-Bachy (1980). The stone columns diameter equals 1.2 m and its length is H_c=7m. The geotechnical parameters of weak soil and column material are given in Table 1. Those parameters are:
γ: Total unit weight; φ: Friction angle; C: Cohesion; E: Young's modulus; ν: Poisson's ratio; G: Shear modulus; K: Bulk modulus.

Bouassida &Hazzar (2012) investigated this case study; they checked that the executed improvement area ratio IAR = 35% was quite overestimated on the basis of averaged recorded settlement of 3.5 cm at the periphery of the tank during water proof test.

Table 1 Geotechnical parameters of constituents of the reinforced soil described by the Mohr Coulomb constitutive law

Parameter	Unit	Soft soil	Stone column
γ	kN/m^3	17	18
φ	degree	0	42
C	kPa	25	0
E	kPa	3600	36000
ν	_	0.33	0.33
G	MPa	1.35	13.53
K	MPa	3.53	35.29

The settlement of storage tank of diameter 54 m is estimated as a function of the applied surcharge load at the surface of the reinforced soil. Figure 2 summarizes the predictions of the settlement by the UCM, analytical methods and the FLAC 3D code both assuming the linear elastic behavior. Note those settlement predictions do not take into account the improvement in stiffness of soft soil due to the stone column installation. This improvement enhances the Young modulus of soft soil and thus leads to more settlement reduction (Ellouze et al., 2016).

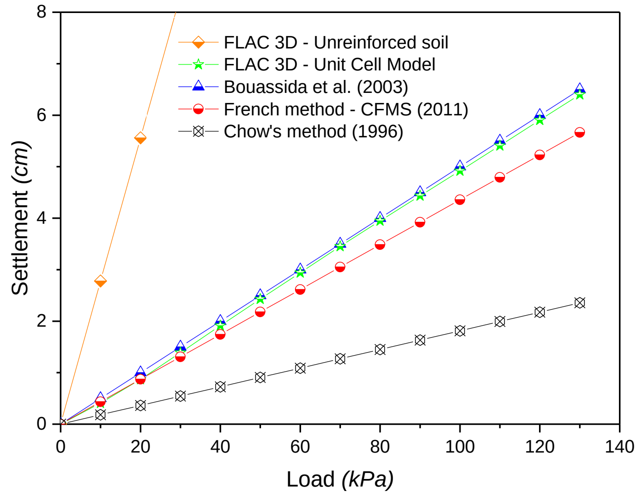

Figure 2 Predictions of settlements in linear elasticity by the unit cell model

Settlement predictions by the FLAC 3D code and the variational approach proposed by Bouassida et al. (2003) are quite identical. In turn, lower settlements are obtained by the French method (CFMS, 2011); this result is expected because of the use of the oedometer modulus for the weak soil rather than its Young modulus. Bouassida (2016) confirmed this result by performing 2D and 3D numerical models of reinforced soil which led to similar predictions of settlements as obtained by the Columns 1.01 software.

Chow's prediction gives the lowest settlement prediction (Chow, 1996). In fact, this method assumes zero horizontal displacement everywhere in the reinforced soil. Therefore, the oedometer moduli of constituents of reinforced soil prevail. The corresponding settlement prediction is largely lower than predictions by other methods (Bouassida and Carter, 2014).

2.2 Group of Stone Columns (GSC)

Figure 3 shows the three suggested 3D models of the soil reinforced by a group of stone columns. The horizontal displacement is zero at lateral border of the three models of reinforced soil. Such assumption warrants that the numerical settlement predictions are not affected. In fact, from prior numerical investigations it is recommended fulfilling the condition in having the ratio between the width of loaded area to that of the lateral area of numerical model less than one third. In fact this ratio equals 0.2; 0.25 and 0.3 for the models shown in Figures 3a - 3b and 3c, respectively. At the lower side of 3D models horizontal and vertical displacements are zero. Tabchouche et al (2017) investigated similar modeling to analyze the behavior of reinforced soil by stone columns in oedometer conditions.

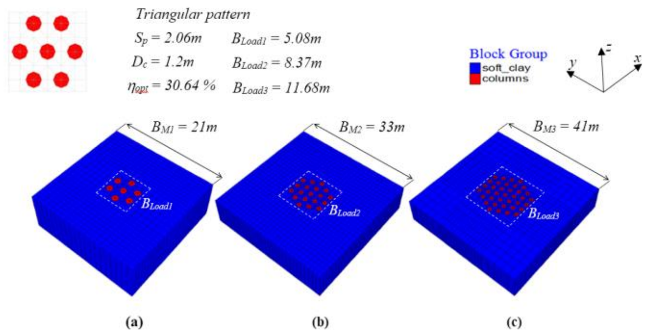

Figure 3 Finite difference discretizations of soil reinforced by a group of 7, 19 and 37 stone columns with equal improvement area ratio; η = 30.64%

The value of optimized improvement area ratio η = 30.64 % is determined by using the Columns 1.01 software (Bouassida &Hazzar, 2012) on the basis of allowable settlement equals 6 cm.

The software Columns 1.01 enables to capture the optimized improvement area ratio by combining the verifications on allowable bearing capacity and given allowable settlement of the foundation on reinforced soil by columns. The inherent methodology of design embodied in Columns 1.01 software was detailed by Bouassida and Carter (2014). The characteristics of the generated meshes are presented in Table 2.

Table 2 Characteristics of stone columns models implemented by the FLAC 3D code

Modeling number	Number of stone columns	Finite difference zones	Number of grid Points	Number of computation iterations
1st	7	1680	1575	2722
2nd	19	4592	4215	3146
3rd	37	8960	7815	5926

The variation of the settlement reduction factor β, as a function of the surcharge load is analyzed for two reinforcement configurations. Geotechnical properties summarized in Table 1 are again considered for constituents of reinforced soil.

Figure 4 shows that the settlement reduction factor calculated, in the ranges 80 to 130 kPa of applied load, from numerical results of the three numerical models of reinforced soil by a group of stone columns varies from 2.2 to 3.2. Further, more settlement reduction is predicted when the number of reinforcing columns increases.

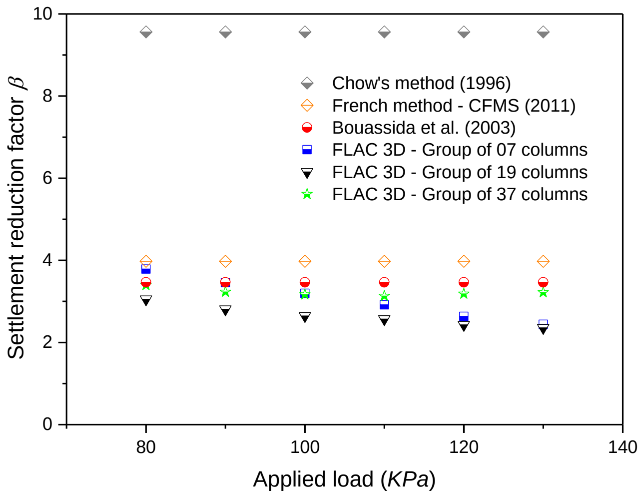

Figure 4 Estimation of settlement reduction factor vs applied load

It is also pointed out, from Figure 4, that the settlement reduction factor is seen quite identical by the method proposed by Bouassida et al. (2003) and the 3D numerical model using a group of 37 stone columns. Indeed, the relative difference between these predictions of ±2.5% is negligible. Hence, it can be concluded that, using 3D modeling of soil reinforced by a group of columns, the inherent settlement reduction factor is not affected by the number of reinforcing columns. The variation of improvement area ratio solely affects the settlement prediction.

The Chow's method (Chow, 1996) always gives the lowest predictions of the settlement reduction factor because of the assumption taken in this method of zero horizontal displacements over all the reinforced soil (Bouassida and Carter, 2014).

2.3 Equivalent Concentric Crowns (ECC)

The group of end-bearing stone columns can be modeled by equivalent concentric stone crowns (Ellouze and Bouassida, 2009 and Ellouze et al., 2016). This option provides easier handling of input mesh data when performing the numerical model by FLAC 3D code.

The thickness e_{Cr} (i), of the equivalent concentric crown (ECC) of area A_{Cr}(i) is deduced from the condition of equal area with that of a group of stone columns A_{GC}(i).

Then, the equivalent thickness e_{Cr} of the crown is deduced as:

$$e_{Cr(i)} = \left(N_{(i)} \times \frac{\pi \times D_c^2}{4} \right) \Big/ \left(2 \times \pi \times i \times S_p \right) \tag{5}$$

A_{Cr} (i) : Area of the equivalent concentric crown ECC n° ''i''.
e_{Cr} (i) : thickness of the equivalent concentric crown ECC n° ''i''.
i×Sp : axis to axis spacing between the central stone column and stone columns located on ECC n° "i".
N(i) : number of stone columns located on the circumference of the crown numbered i.

Figure 5 illustrates three models of a group of stone columns and their corresponding ECC models. As an example, from Figure 5a the thickness of ECC n° 1 is determined by setting: i= 1, N(1) = 6; S_p = 2.06 m and D_c = 1.2 m.

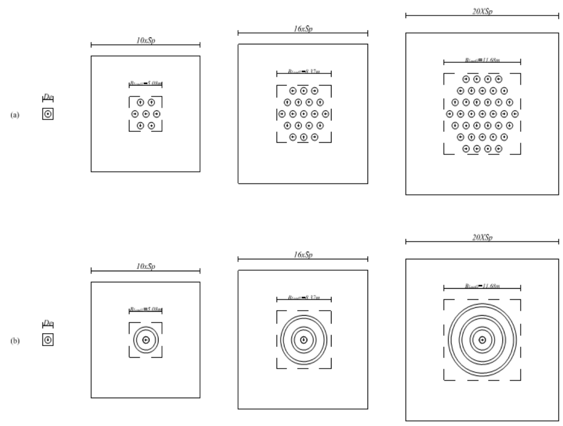

Figure 5 Finite difference discretizations: (a) group of stone columns; (b) equivalent concentric stone crowns

Table 3 presents the geometrical characteristics of the numerical models implemented by the FLAC 3D code.

Table 3 Characteristics of the equivalent concentric crowns implemented by the FLAC 3D code

N° of equivalent concentric crowns	**Thickness [cm]**	**Number of finite difference zones**	**Number of grid points**	**Number of computation iterations**
1st	52.42	3136	3375	5644
2nd	52.42	4928	5295	6237
3rd	52.42	8512	9135	8560

The variation of settlement predictions versus the applied load using the group of stone columns models and the corresponding ECC respectively are displayed in Figures 6-7.

Figure 6 shows that the settlement prediction decreases when the number of stone columns decreases as well. The difference in settlement predictions is more significant when the value of the surcharge load is greater than 100 kPa, the more likely to happen in current stone columns project. The increase in the number of stone columns, even at constant IAR, increases the contact points between the foundation and reinforcing elements where more concentration of vertical stress occurs. This explains the predicted reduction of settlement foundation.

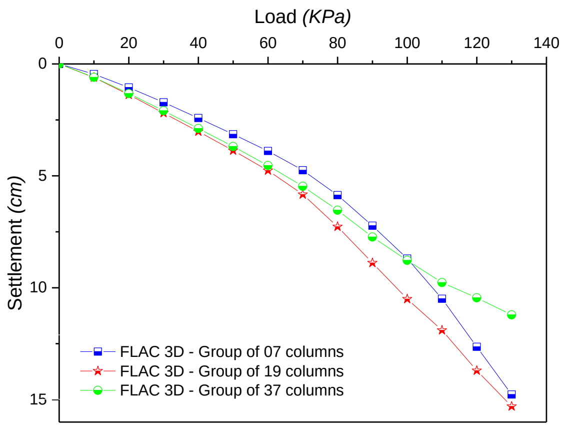

Figure 6 Settlement prediction of column-reinforced foundation with a group of 7, 19 and 37 stone columns vs applied load

Figure 7 displays the settlement variation versus applied load when the three ECC models of reinforced soil are considered. From this figure it is noted that the lowest settlement prediction is obtained from the model using one ECC. Whilst by the two and three ECC models the settlement prediction is almost identical.

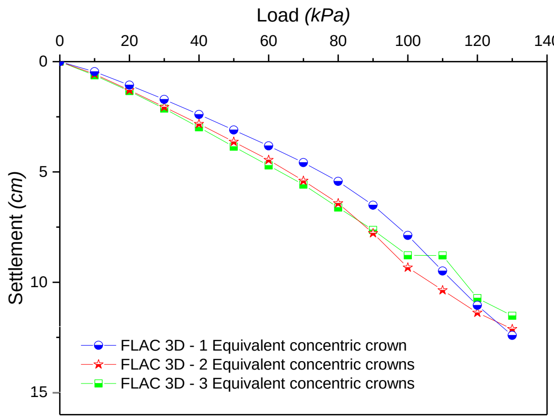

Figure 7 Load-settlement of column-reinforced foundation with 1, 2 and 3 equivalent concentric crowns

Figures 8-9 and 10 compare between the predictions of settlement vs the applied load by the group of stone columns models and the corresponding ones using the ECC, i.e. seven stone columns with respect to one ECC; nineteen stone columns with respect to two ECC and thirty-seven stone columns with respect to three ECC.

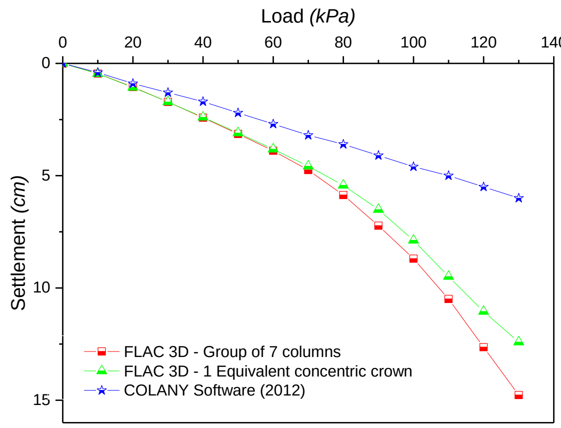

Figure 8 Variation of settlement prediction versus applied load for reinforcement models of a group of 7 columns and one equivalent concentric crown

It is well noted that the settlement predictions by the ECC models are lower than those obtained by the respective group of stone columns' models.

This difference in settlement reduction decreases as the number of stone columns or ECC increases. Figure 8 shows, for a working load of 130 kPa, that the difference between settlement predictions by the group of 7 stone columns and one ECC equals 2 cm. Figure 10 shows this difference is reduced to 0.9 cm when comparing the settlement predictions by the group of 37 stone columns and three ECC for and applied load q = 110 kPa.

From Figure 10 it can be concluded that equal settlement predictions are obtained either considering the model of reinforcement using 37 stone columns or three ECC.

Further, from Figures 8-9 and 10 it is also agreed that once the UCM is adopted the settlement prediction by the Balaam and Booker (1982) method's, implemented in the COLANY program (Balaam, 2012) significant lower settlement predictions are obtained in comparison to the 3D numerical models generated by the FLAC 3D program.

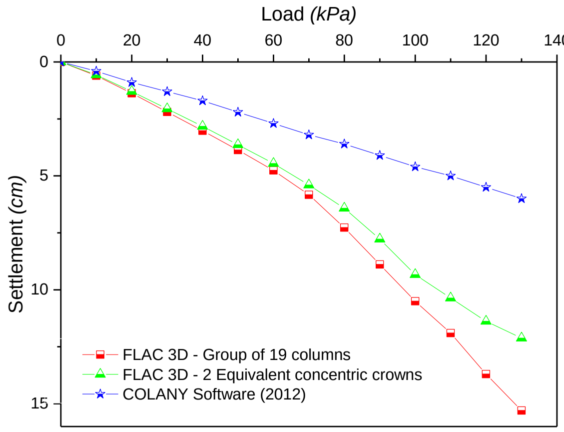

Figure 9 Variation of settlement prediction versus applied load for reinforcement models of a group of 19 columns and two equivalent concentric crowns

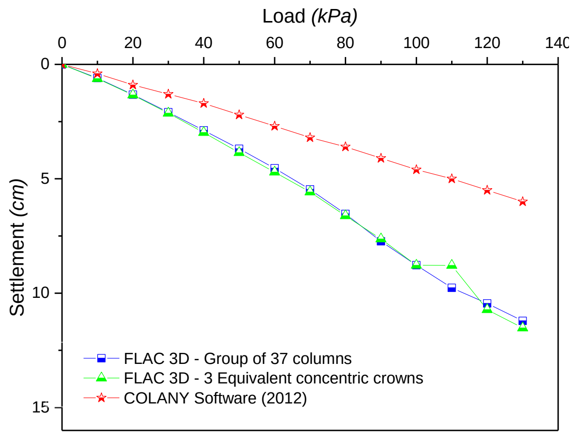

Figure 10 Variation of settlement prediction versus applied load for reinforcement models of a group of 37 columns and three equivalent concentric crowns

2.4 Comments on total adhesion assumption between the weak soil and reinforcing stone columns

There is a geometrical difference between the studied models of groups of stone columns and the corresponding ECC that is the contact area between those reinforcing elements and the surrounding weak soil. Along this contact area it was assumed total adhesion between the two materials. One can easily verify that the contact area, of given model of a group of stone columns, is much lower than the contact area of the corresponding ECC model. Since the settlement predictions were found quasi-identical by the models of a group of stone columns and corresponding ECC models it follows the settlement response of foundation on reinforced soil is not affected by the assumed total adhesion between stone columns and surrounding weak soil. However, Frikha et al. (2015) pointed out that the measured ultimate bearing capacity of soft soil reinforced by a group of sand columns, at fixed low improvement area ratio, increases when the number of columns also increases.

3. VALIDITY OF FLAC 3D RESULTS

Figure 11 shows the iso-values of vertical and horizontal displacements throughout the numerical model of soil reinforced by stone columns. It is clear that horizontal and vertical displacements close to the lateral border are almost zero. Such prediction confirms that the settlement profile of rigid raft is not affected by the assumed zero horizontal displacements at the lateral border of the suggested 3D model of reinforced soil.

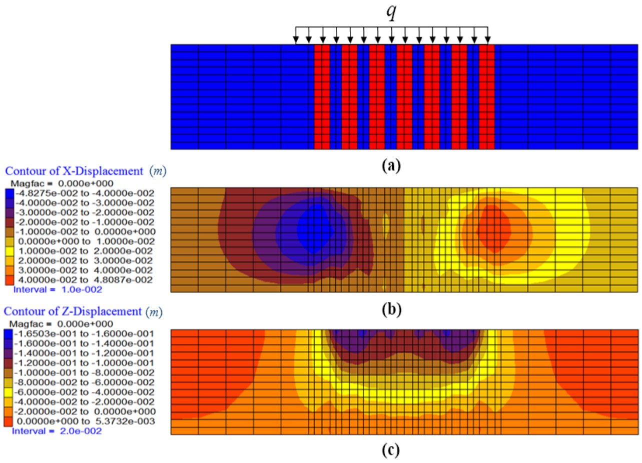

Figure 11 (a) Cross section of ground reinforced by stone columns generated by the FLAC3D code; (b) Iso-values of the horizontal displacement under applied loadof 130 kPa; (c) Iso-values of the vertical displacement under applied load of 130 kPa

The end-bearing stone columns are made up of free-draining material having enhanced hydraulic conductivity, they behave like vertical drains. Hence, the consolidation of initial compressible soil is accelerated. Under progressive applied load (construction of oil tank) the settlement of reinforced will be almost completed at the end of construction since any induced excess pore pressure will be dissipated instantaneously. This observation was witnessed for the studied case history (Gambin, 1992). This is to conclude that even idealized soil condition and total stress analysis was carried out using the FLAC 3D code the behavior of reinforced soil is unique either in short term or in the long term case.

The evolution of this consolidation settlement of soil reinforced by end-bearing draining columns has been predicted by a linear poro elastic model suggested by Guetif& Bouassida (2005) and, later on, was programed in Columns 1.01 software (Bouassida &Hazzar, 2012).

4. BULGING EFFECT ANALYSIS BY THE 3D MODELLING USING THE GROUP OF STONE COLUMNS

Figure 11a represents the cross vertical section of the reinforced soil modeling at half of the width of rigid raft equals 20 Sp as shown in Figure 5a. Figure 11b clearly shows the bulging effect provided the 3D modelling using actual the cylindrical stone columns. Indeed, at midst depth of the reinforced soil the horizontal and vertical displacements, at the vertical edge of rigid raft, are 4.8 and 4.0 cm, respectively. The horizontal displacement is greater than the vertical one, thus the lateral expansion prevails against the vertical displacement.

Figures 12a-b show the distributions of vertical and horizontal stresses within the reinforced soil mass. At the surface of reinforced soil the stress concentration ratio varies between the axis of rigid raft to its border in the range of 0.7 to 1.35. This result indicates that the stress concentration factor as predicted from a truly 3D modelling of soil reinforced by a group of stone columns in averaged value approximates one. That is significantly different from suggestions from the unit cell model.

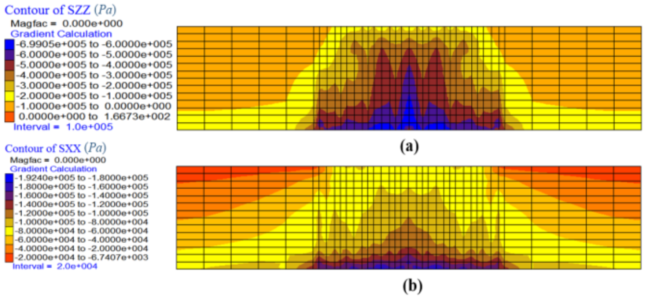

Figure 12 (a) Iso-values of horizontal stress under applied load of 130 kPa; (b) Iso-values of vertical stress under applied load of 130 kPa

5. CONCLUSIONS

In this paper, 3D numerical models have been proposed to evaluate the settlement of a rigid foundation resting on soil reinforced by a group of end-bearing stone columns.

Three numerical models, with equal improvement area ratio, of a group of stone columns installed in a triangular pattern have been built by the FLAC 3D code. Then, three models of reinforced soil have been suggested by using equivalent concentric stone crowns. Parameters of the reinforced soils were calibrated from measured settlement of Tunisian stone columns case history.

The main findings that resulted from the numerical investigation are summarized below.

- Load-settlement curves obtained by the FLAC 3D code confirmed the underestimation of settlement predicted by the unit cell model. This result is attributed to the confinement resulting from the assumed zero horizontal displacement at the border of the UCM.
- When adopting the reinforcement by a group of stone columns, the increase in number of stone columns (from 7 to 37) does not greatly affect the predictions of settlement, but it provides much better settlement reduction factor. This behavior is attributed to a much better concentration of vertical stress when increasing the number of stone columns. Further, the settlement predicted by the variational method suggested by Bouassida et al. (2003) is close to that obtained from the FLAC 3D model with 37 stone columns.
- When adopting the reinforcement by concentric crowns models ECC 1, 2 and 3 the difference in settlement with respect to equivalent models of group stone columns, respectively, decreases when the number of increases from 7, 19 to 37.
- The settlement predictions by the group of 37 stone columns and 3 equivalent concentric crowns models are quite similar. Therefore, the study behavior of foundation resting on soil reinforced by a group of stone columns, in terms of settlement prediction, is easier when performing numerical FLAC 3D models using the equivalent stone crowns reinforcement. In fact, when the number of stone columns becomes higher than 37 an easier handling of input data is provided by the use of equivalent stone crowns. This numerical recommendation is more agreed because the assumed total adhesion between the columns and equivalent crowns does not affect the prediction of the settlement of foundation on reinforced soil.
- The bulging effect has been proven from the predicted horizontal and vertical displacements, at the border of rigid raft at midst depth of the reinforced soil. Whilst, the concentration of vertical stress was found present only at the border of rigid raft. In turn, under the axis of rigid raft the predicted behavior of soil reinforced by a group of columns did not show the concentration of vertical stress.

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