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Comparison of Numerical Analyses of Behaviour of Column-Reinforced Foundations

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ABSTRACT: This paper studies the prediction of behaviour of foundations resting on a soil reinforced by sand and stone columns. The preliminary design is based on an optimized improvement area ratio predicted by the methodology proposed by Bouassida & Carter (2014). The prediction of the behaviour of the reinforced soil is predicted by numerical computations carried out by Plaxis V9.2D and FLAC3D codes in plane strain and axisymmetric conditions. A Tunisian case history of oil tank is investigated. When assuming the linear elastic behaviour for constituents of reinforced soil, it is noted that the predictions of settlements given by Columns 1.01 software are in good agreement with numerical results obtained by Plaxis and FLAC3D codes. Comparison between those approaches shows the validity of results using the Columns 1.01 software. By adopting the Mohr-Coulomb failure criterion for columns material and the hardening soil model for soft clay, the evolution of long term settlement predicted by Plaxis code showed the acceleration of the consolidation of the compressible soft clay due to the enhanced drainage property of column material.

KEYWORDS: Behaviour, Case history, Settlement, Numerical, Sand column, Soft clay.

1. INTRODUCTION

The study of the behaviour of engineering structures built on soil reinforced by columns increasingly knew, since the last decades, several contributions. As for other geotechnical applications, the development of finite element and finite difference codes in conjunction with advanced constitutive laws for soils enhanced the accuracy of numerical computations using either 2D or 3D modelling of reinforced soil by a group of columns (Six et al, 2012). When dealing with columnar reinforcement of soft soil, the evolution of settlement resulting from the acceleration of consolidation is with high importance in regard to long term stability of the studied structure. In this regard, among several contributions, Han and Ye (2001) demonstrated the stress transfer from the soil to stone columns and dissipation of excess pore water pressures due to drainage and vertical stress reduction during the consolidation.

Six et al. (2012) studied the effect of horizontal stress in reinforced clay by expanded stone columns. Those authors carried out finite element calculations to predict stone columns behavior using analytical methods and conventional engineering methods. It was found that the at-rest earth pressure coefficient K0 is related to the initial state of stresses caused by the compression of in-situ soil due to the installation of column material. The importance of defining the initial state of stress due to stone columns installation is of big importance for the design of a stone column foundation.

In those existing contributions the improvement area ratio was adopted arbitrarly.

In this paper, two main goals are targeted. First objective is to discuss the usefulness of the linear elastic behaviour in describing the behaviour of constituents of reinforced soil by columns. Accordingly, the settlement predictions by Columns 1.01 software based on an optimized area ratio (Bouassida & Hazzar, 2012) are compared with results predicted by the group of columns modelling in linear elasticity. The comparison between settlement predictions, obtained by the linear elasticity model and Mohr Coulomb failure criterion, is made regardless the consolidation aspect. Second, the influence of columns material is foreseen when the consolidation phenomena is taken into account when the reinforcement of soft soil is considered.

2. BEHAVIOUR OF REINFORCED SOIL

The settlement prediction using the linear elastic behaviour refers to the short term condition of reinforced soil. Whilst, adoption of the consolidation option embodied in Plaxis and FLAC codes when the reinforcement of soft clay by end-bearing columns made up of drained material (clean sand and gravel mixtures having good permeability higher than 10-4 cm/s) is considered the corresponding settlement also refers to the long term behaviour due to the acceleration of consolidation provided by the columns that play the role of vertical drains (Bouassida & Carter, 2014).

2.1 Foundations on Compressible Clays Reinforced By End-Bearing Columns

The Tunisian case study ''Oil Tank at La Goulette''is considered to carry out numerical computations using the FLAC3D and Plaxis codes. The reinforcement by end-bearing sand columns of soft clay layer of 10 m thickness has been considered for an applied surcharge load of 80 kPa by a circular tank of 30 m diameter. Consider the allowable settlement of reinforced soil equals 10 cm, the optimized Improvement Area Ratio (IAR), as determined by the Columns 1.01 software, is 29.95% that was executed by 729 sand columns of 0.6 m in diameter with axis to axis spacing of 1.06 m installed in triangular pattern.

Figure 1 depicts the FLAC 3D numerical model of reinforced soil which consists of a central row crossing the central part of tank with dimensions: 30.74 m in length along x direction; 2.12 m in width along y direction and 10 m in depth as length of end-bearing sand columns (Bouassida, 2016). This reinforced soil model comprising 29 columns is modelled by generated mesh constituted by 18320 finite element zones and 16947 grid-points. The reinforced soil model subjected to uniform load of 80 kPa has the following boundary conditions: horizontal displacement along x and y directions is assumed zero; horizontal and vertical displacements are zero at the stratum depth level. Computations were carried out by adopting the elastoplastic behaviour described by the Mohr-Coulomb model without taking into account the primary consolidation option. The geotechnical parameters of the numerical model are given in Table 1.

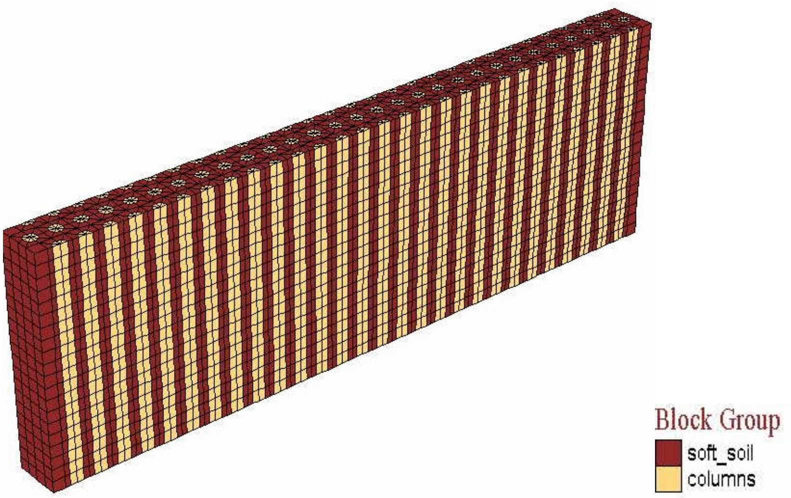

Figure 1 The FLAC 3D numerical modelling of reinforced soil: La Goulette case study, Tunisia

Table 1 Geotechnical parameters of the numerical model generated by the FLAC 3D code

Parameters	Thickness or length (m)	E (MPa)	υ	φ (°)	C (kPa)	γ (kN/m^3)
Columns material	10	20	0.33	38	0	18
Soft soil	10	2.0	0.33	0	24	17

The evolution of the vertical displacement at the surface of the unreinforced soil vs the number of iterations, at centreline of tank, is plotted in Figure 2 that indicates a maximum vertical displacement of 20.4 cm. The evolution of vertical displacement of reinforced soil at centreline of tank versus number of iterations is plotted in Figure 3.

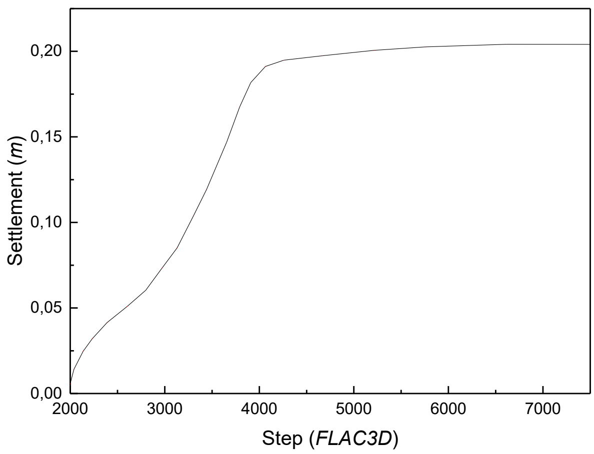

Figure 2 Evolution of vertical displacement of unreinforced soil.

Table 2 summarizes the predictions of settlement as obtained by the FLAC3D code and by the methods incorporated in Columns 1.01 software (Bouassida & Hazzar, 2012) all assuming the linear elastic behaviour both for the initial soil and column material.

It is noticed that the settlement prediction by FLAC 3D code is close to the settlement prediction obtained by the analytical method proposed by Bouassida et al (2003) which consider the modeling of a group of columns similarly as the one used by the FLAC3D code in this generated models. The relative difference between the predicted settlements is less than 1.2% that is quite negligible.

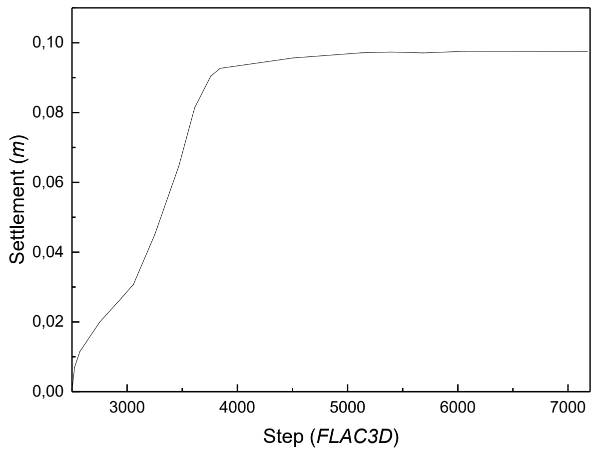

Figure 3 Evolution of vertical displacement of reinforced soil.

Table 2 Settlement predictions obtained by the FLAC3D and Columns 1.01 software

Method of prediction	FLAC 3D code	Bouassida et al. (2003)	French method (2011)	Balaam & Booker (1981)
Unreinforced soil	20.4	38.37	20.8	20.8
Reinforced soil	9.88	10.0	8.6	7.48

Considering the elastoplastic behavior (regardless the consolidation option) of the constituents of the reinforced soil by columns, the numerical results obtained by the FLAC3D code have confirmed the results provided by the optimized methodology of design of column-reinforced foundations embodied in the Columns 1.01 software. Although the elastoplastic behaviour for constituents of reinforced soil by columns was assumed by the numerical FLAC 3D code, the results were found identical to those predicted by the new methodology of design that considers the linear elastic behavior for constituents of reinforced soil (Bouassida & Carter, 2014). Such result can be explained by the fact that settlement prediction is essentially foreseen under admissible loads that do not induce large deformation within the reinforced soil. It follows the predictions both by linear elastic and elastoplastic constitutive laws can be quite similar.

2.2 Comparison between Numerical Predictions in Plane Strain And Axisymmetric Analyses

The plane strain condition can be adopted for structures having a current cross section that extends on a quite length as compared to the dimensions of the cross section of studied structure. The linear loading condition of such structures shows that the displacement in the perpendicular direction to the cross section of the considered structure is negligible. In turn, axisymmetric analysis applies for structures having geometrical and loading symmetries with respect to a revolution axis. The common property for plane strain and axisymmetric analyses relies on their inadequate modelling of a truly 3D structure.

The Tunisian case study of oil tank (La Goulette) is now considered to compare the predicted behaviour of unreinforced and reinforced soft clay of Tunis by sand columns both in plane strain and axisymmetric conditions. This numerical study has been conducted by the Plaxis V9.2D finite element code adopting the hardening soil model (HSM) as constitutive law for Tunis soft clay. The simulation of the behaviour of the Tunis soft clay specimens subjected to oedometer and triaxial tests showed that the HSM predictions are in agreement with the measured data rather than predicted results obtained by the Cam-Clay modified model (Klai, 2014).

Performing numerical computation in plane strain condition passes by the determination of the equivalent width, B, of squared tank that has the same area as the circular tank of radius R = 15 m, $B=\sqrt{\pi}R=26.587m$ (Klai et al, 2015).

Predictions by the HSM (plane strain condition)

The variation of the settlement of the unreinforced soil at the boundaries of the oil tank, illustrated in Figure 4 shows a maximum consolidation settlement of 4.2 cm. The predicted maximum consolidation settlement is 21.8 cm at the centerline of the tank, the consolidation time approaches ten years. It is clearly seen that the long term settlement due to the consolidation of soft clay is slightly larger than the settlement of 20.8 cm predicted by different methods that adopt the linear elastic behaviour (see Table 2).

As illustrated in Figure 4, the differential settlement of the tank is truly problematic for the stability of the tank. The normalized differential settlement is of about 0.3% that exceeds notably the allowable limit of 0.1%. Therefore, to avoid excessive settlements which can compromise the stability of the tank, the need of column-reinforcement of Tunis soft clay is strongly recommended to reduce the settlement and to accelerate the consolidation by choosing a drained column material like sand with enhanced hydraulic conductivity.

Similar predictions were confirmed throughout the study of other case study presented in very recent work by Bouassida (2016).

The behaviour of soft clay reinforced by sand columns in plane strain condition has been analysed using the perfect elastoplastic law and the Mohr-Coulomb model have been adopted for the sand as constitutive column material with geotechnical properties displayed in Table 4.

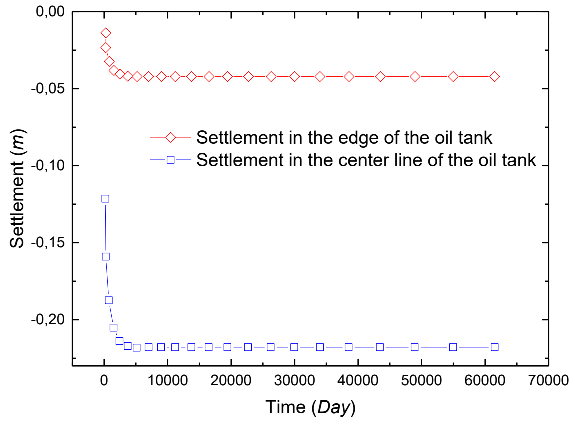

Figure 4 Evolution of the settlement of the unreinforced soil using plane strain modelling

Table 4 Geotechnical properties of initial soil and constitutive column material

Parameters	Thickness or length (m)	*E* (MPa)	*υ*	*φ* (°)	*C* (kPa)	γ (kN/m³)
Sand (columns)	10	20	0.33	38	0	18
Tunis soft clay	10	2	0.4	0	24	17

The variation of the consolidation settlement, in plane strain condition, is plotted in Figure 5 both at the centerline and at the border of the oil tank where predicted values are 7 cm and 3.8 cm respectively.

The quasi constant distribution of settlement at the surface of the reinforced soil is partially owed to the presence of blanket drainage layer. One can consider that the differential settlement equals the difference between predicted settlements at the centerline and the border of the oil tank. The comparison between Figures 4 and 5 well shows that the reinforcement by sand columns greatly reduces the differential settlement from 17.7 to 3.2 cm that plays an important benefit for the stability of the oil tank.

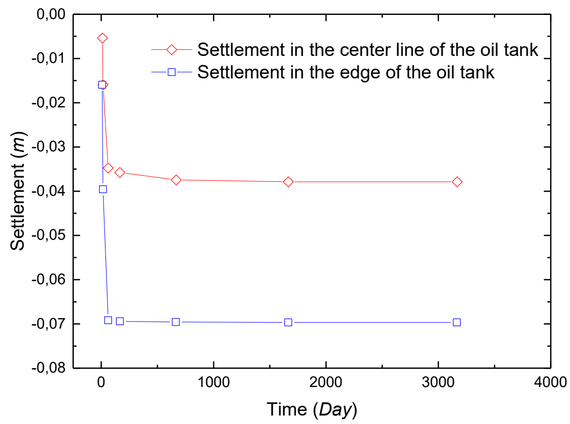

Figure 5 The evolution of the consolidation settlement of the reinforced soil (plane strain condition)

Predictions by the HSM (axisymmetric condition)

The axisymmetric study is carried out comparing the predicted 2D behaviour of unreinforced soil and reinforced soil by sand columns by implementing numerical computations using the Plaxis code. The adopted parameters of the hardening soil model for Tunis soft clay are given in Table 5.

Table 5 Parameters of the hardening soil model for Tunis soft clay

γ_c [kN/m^3]	e	E' [kPa]	G [kPa]	ν_c	$E_{oed,c}$ [kPa]	φ_c [°]	k_h=k_v [m/day]
18	0.5	20,000	7519	0.33	29,630	38,0	10

The evolution of the consolidation settlement, versus time, at the surface of the unreinforced soil is illustrated in Figure 6 that shows the primary consolidation is expected to end within 12.5 years. The maximum settlement at the centerline of tank equals 27 cm that exceeds the predicted settlement in plane strain condition. The same remark holds for the predicted settlements at the border of the tank which are 8.3 cm and 7 cm, respectively in axisymmetric and plane strain conditions. However, when adopting the consolidation procedure, it was found that the end of the primary consolidation settlement remains unchanged (12.5 years) both for the plane strain and axisymmetric analyses.

The evolution of the consolidation settlement at the surface of the reinforced soil by sand columns (axisymmetric study) is plotted in Figure 7. From this figure, it is noticed that the settlement at the centerline of the tank of 9.4 cm is greater than the predicted value of 7 cm in plane strain condition (Figure 5). The same remark holds for the predicted settlements at the border of the oil tank: 4.5 and 3.8 cm, respectively, in axisymmetric and plane strain conditions.

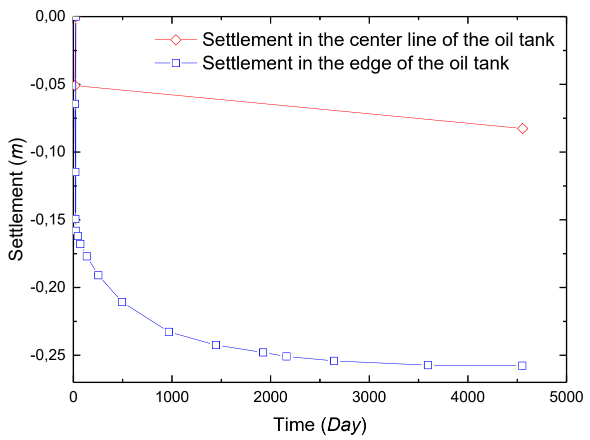

Figure 6 Evolution of the consolidation settlement of the unreinforced soil (axisymmetric condition)

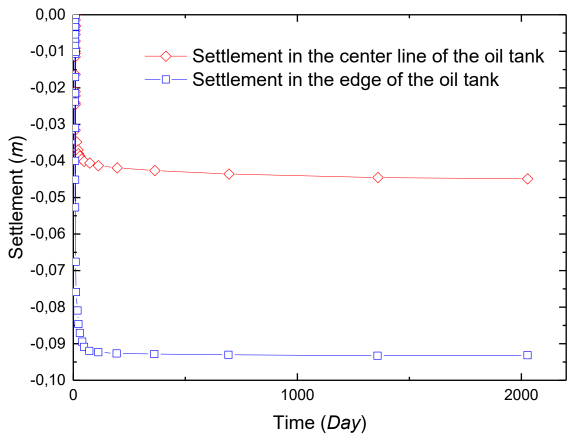

Figure 7 Evolution of the consolidation settlement at the surface of the reinforced soil

Table 6 summarizes the predicted settlements of the consolidation at the centerline of the oil tank of La Goulette both in plane strain and axisymmetric conditions (performed by the Plaxis V2.9 and the 3D model generated by the FLAC 3D code). It is noticed that the predicted settlements of the unreinforced soil are quite similar with the plane strain computation using Plaxis and FLAC3D programs. In turn, axisymmetric study using the Plaxis code leads to an overestimated prediction of the consolidation settlement of the unreinforced soil. For the case of the reinforced soil, it is found that the plane strain condition slightly underestimates the settlement prediction compared to that obtained by Plaxis software in axisymmetric condition and the one obtained by FLAC3D model. It is concluded that comparable results are obtained using any computational tools (Plaxis or FLAC) regardless of the adopted model either 2D (plane strain and axisymmetric conditions) or 3D.

Table 6 Settlement predictions at centreline of the La Goulette oil tank by Plaxis V2.9 and FLAC 3D codes.

Numerical tool	Option computation	Unreinforced soil (cm)	Reinforced soil (cm)
Plaxis V9.2D	Plane strain	21.8	7.0
Plaxis V9.2D	Axisymmetric study	24.8	9.4
FLAC 3D	3D model	20.4	9.88

3. CONCLUSION

This paper focused on the study of the behaviour of foundations installed on compressible soils reinforced by sand columns. A Tunisian case study has been investigated by performing numerical computations with the Plaxis V9.2 and the FLAC 3D codes.

All those methods consider the linear elastic behaviour both for the initial soil and column material. It is noticed that the settlement predictions obtained with the FLAC 3D code are close to those obtained with the analytical method proposed by Bouassida et al (2003). The latter uses the group of columns model as for the FLAC3D code. The relative difference between these predictions, of 0.59 % and 3.74% respectively for the unreinforced soil and the reinforced soil, are negligible. This first example confirms the usefulness of analytical methods of settlement predictions programmed within the Columns 1.01 software that provides the optimized reinforcement.

It is noticed that the difference between predicted settlements of unreinforced soil is not significant; therefore the use of any computational tool (Plaxis or FLAC) or any study hypothesis (plane strain or axisymmetric study) leads to comparable results from which the need of reinforcement by columns can be justified. In turn, when dealing with the modelling of reinforced soil, it is revealed that the plane strain condition slightly overestimates the settlement prediction. Indeed, such hypothesis is not realistic for cylindrical structures. The axisymmetric condition can be adopted since its settlement prediction is close to that obtained a 3D modelling of soil reinforced by columns.

Main finding was the stability of an oil tank built soft soil reinforced by sand columns is warranted by minimised differential settlement between the centre and the border of tank. Such prediction favouring quasi uniform settlement distribution over the tank area is more confirmed when a drainage (or blanket) layer is spread at the surface of reinforced soil.

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