Special Contribution

Optimizing the design of foundations on soils reinforced by columns

Prof. Mounir Bouassida

University of Tunis El Manar. National Engineering School of Tunis.
Head of Research Laboratory Geotechnical Engineering LR14ES03.
BP 37, Le Belvédère, 1002 Tunis. Tunisia

Abstract. Recent rational methodology is presented, in brief, for the design of column-reinforced foundations. Optimizing the design of this type of foundations constitutes the focal point of this paper. The optimization of design is addressed for two reinforcement scenarios: end-bearing and floating columns. For the first scenario, it is shown up that the improvement area ratio can be optimized when the improvement of initial soil stiffness is considered, particularly when the stone column technique is practiced. For the second scenario, the length of floating columns is also optimized considering the admissible rate of consolidation of sub-layers underneath the reinforced soil. Worth mentioning that the recent methodology of design also provides an optimized design, when the improvement of initial soil is not considered and regardless of the column type. Discussion of selected case histories-studies made it possible to sort out the inherent highlights regarding the design of foundations on soils reinforced by columns.

1. Introduction

Several techniques are nowadays practiced to reinforce soft and/or highly compressible deposits. Stone columns, sand-compaction piles and deep soil mixing are among the most popular techniques enabling the increase of bearing capacity (BC), the reduction in settlement and the acceleration of consolidation. Mitigation of liquefaction is also another benefit which can be targeted by using vibro-compaction and stone column techniques.

Recently, a rational design methodology of column-reinforced foundations was suggested, then, implemented for several case studies (Bouassida, 2016a & b). Bouassida & Carter (2014) detailed the inherent methodology of design considering the optimization of area ratio in cases of end-bearing columns. The installation of stone columns enables the improvement of soft clays, namely the modulus of deformation and undrained shear strength, as pointed out by Guetif et al., 2007 and Ellouze et al., 2017. Such an improvement contributes in the reduction of optimized improvement area ratio (IAR) previously determined.

Optimizing the design of column-reinforced foundation can be foreseen into two scenarios. First optimization is related to the improvement area ratio after verification of the BC and settlement criteria (Bouassida & Carter, 2014) for the reinforced soil zone. The merit of proposed methodology relies on the prediction of an optimized area ratio associated to an allowable settlement. Bouassida et al. (2017) checked on the conservative side compared to existing methods of design.

Considering the end-bearing type of columns two cases should be considered depending on the column installation technique. This latter can affect the properties of surrounding initial soil. Indeed, when the stone columns and/or the vibro-compaction are adopted, the installation of column material by lateral expansion induces the consolidation of surrounding soil from which the modulus of deformation and strength resistance are enhanced (Guetif et al., 2007 & Frikha et al., 2013). At less extent, the sand compaction technique also moderately affects the properties of surrounding soil. Contrarily, the equipment of deep soil mixing technique essentially dedicated to very soft clays does not actually affect their parameters (Bouassida, 2016 a & b). Therefore, the optimized area ratio can be reduced when the initial soil properties are enhanced due to the stone column installation technique.

Numerical simulation conducted by Ellouze et al. (2017) highlighted the increase in Young modulus of soft soil after the installation of model comprising seven stone columns in triangular pattern. It is understood that predicting such an improvement is depending on the constitutive model adopted for the soft initial soil (Mohr-Coulomb, Hardening Soil Model or Soft Soil Model).

Second scenario is related to the reinforcement by floating columns which can be considered in cases the stratum layer is very deep. During the last decade; several contributions were dedicated to the analysis of reinforcement by floating columns. Published contributions addressed the determination of bearing capacity, Bouassida et al. (2009) and Fattah et al. (2017), the settlement prediction and the behavior of foundations on soil reinforced by floating columns, Ng & Tan (2014), Shahu & Reddy (2014) and Tabchouche et al (2018). Meanwhile the design oriented to optimized length of floating columns still remains with little interest.

The optimization of columns' length depends on the dimensions of loaded foundation and the parameters of unreinforced layers (Bouassida & Hazzar, 2015). Optimized length of floating columns relies on the admissible long-term settlement of compressible layers underneath the reinforced soil. Based on this criterion, Bouassida & Ellouze (2018) recently reported on the optimization of length of floating stone columns for a Tunisian case study.

This paper aims to give an insight about the optimization of design of foundations on soil reinforced by columns through detailed discussion of case studies including the reinforcement by end-bearing and floating columns as well.

2. Reinforcement using end-bearing columns

2.1 Case history n°1: Oil tank at Zarzis terminal (Tunisia)

This case shows up the optimization of area ratio (AR) without consideration of the improvement of surrounding initial soil, and when such improvement is also considered. Figure 1 displays the oil tank diameter, initial soil properties and stone columns' characteristics.

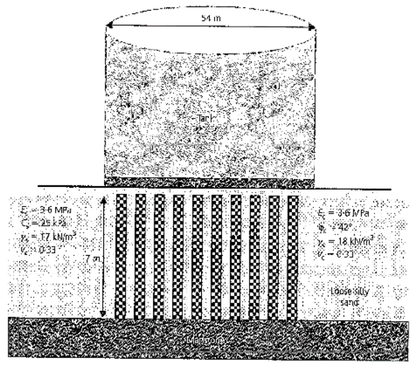

Figure 1 Data of oil tank at Zarzis terminal (Bouassida & Hazzar, 2012)

The practiced AR of 35% was highly conservative because the adopted design method only considered the settlement verification based on the French standard which considers the unit cell model. Bouassida & Hazzar (2012) discussed this case history by implementing the methodology embodied in Columns 1.01 software. Using the project data (Figure 1), it resulted that a significant reduction of area ratio was possible to only install stone columns with an optimized area ratio equals to 30.64 % complying with allowable uniform settlement of 6 cm. This design using the group of columns modelling obviously does not consider the improvement of initial soil (loose silt sand) properties.

Further, settlement gauges installed at the periphery of tank assured the follow up of settlement evolution during tank construction. Recorded averaged settlement, assumed as uniform component, was nearby 4 cm. From this observation it is understood that the reduction of settlement of 2 cm (from predicted to that recorded) can only be attributed to the effect of stone columns installation in the loose silt sand layer. Back calculation of the homogenized Young modulus of reinforced soil (Bouassida 2016a) considering the observed settlement of reinforced soil equals to 4 cm leads to conclude that the Young modulus of loose silt sand layer increased by 40 %. Hence, if the actual admissible settlement of tank foundation was 4 cm, the improvement area ratio can be reduced more than the initially optimized value of 30.64%. The second optimized area ratio can be determined by using Columns 1.01 software. Worth mentioning that predictions by Columns 1.01 software, obtained in linear elastic framework, were in fair agreement with numerical predictions obtained by FLAC3D code (Bouassida et al., 2017). The behavior of rigid raft resting on soft soil reinforced by group of end-bearing stone columns was simulated by FLAC 3D code. From obtained results, the induced bugling effect by lateral deformation surrounding the reinforced soil was explained (Tabchouche et al., 2018).

Guetif et al. (2007) used the data of Damiette project (Naama Engineering and consulting, 2001) and implemented the composite cell model, shown in Figure 2. Implementing numerical 2D computations by Plaxis software those authors proposed predictions confirming such quantification of increased Young modulus of soft clay and the extent of improved zone. Laterally expanded stone column was simulated by the "dummy material" procedure detailed by Debats et al. (2003) including the horizontal consolidation of soft clay. From this latter, the average estimated increase in Young modulus was by 1.3 times, the extent of improved soft clay approximated three times the radius of SC. This case study well illustrates how the design of foundation on soil reinforced by SC can be optimized, first, by implementing the

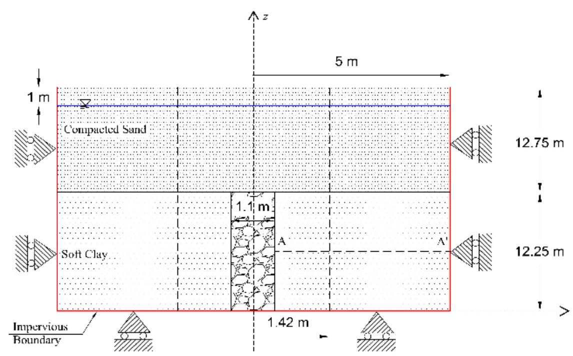

Figure 2 Composite cell model (Guetif et al., 2007)

recent methodology, and, second, by considering the improvement due to the primary consolidation of soft clay which resulted from the installation of stone column by lateral expansion.

2.2 Case study n°2: Damiette project

Ellouze et al. (2017) recently investigated the improvement of Young modulus of soft soil by implementing numerically the “Dummy material” procedure for the reinforcement by a group of end-bearing columns. The numerical model, shown in Figure 3, comprises central column surrounded by six columns installed in triangular pattern (Ellouze & Bouassida, 2009). Those six columns, reduced to an equivalent circular crown, have the same reinforcing area, so that the axisymmetric condition to run Plaxis 2D numerical computations is applicable, as for the case of the composite cell model. The benefit of this model is to look for the optimized spacing between the columns which is determined from the profile of horizontal displacement (outward for the central column; inward for the equivalent crown) induced by the simulated lateral expansion of soft clay. Numerical computations were run by adopting the Mohr-Coulomb and hardening soil modelling for soft clay, and the Mohr-Coulomb constitutive model for the columns material.

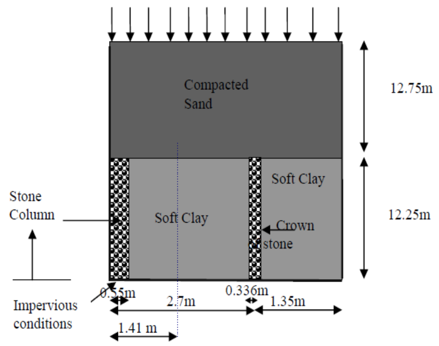

Figure 3 Numerical model of group of stone columns

The main insight from the study by Ellouze et al. (2017) was to estimate the reduction of area ratio by comparing the two cases: without improvement of soft clay and when this improvement was considered. Figure 4 displays the reduction of area ratio when modeling the soft clay by the Hardening Soil Model. From this figure, one can note how significant the reduction of the initially optimized area ratio is when the improvement of soft soil is considered. In this regard, learned lesson from a French case history reported by Debats et al. (1999), was, after stone columns installation, a rest time revealed necessary to make possible the improvement of initial soil by laterally expanded stone columns.

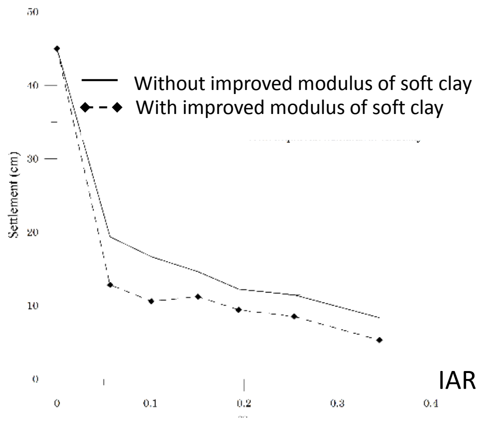

Figure 4 Variation of settlement versus improvement area ratio

Presently, at the National Engineering School of Tunis, the investigation on this subject is oriented to analytical prediction of the reduction in area ratio when considering a given rate of improvement of soft soil.

3. Reinforcement using floating columns

This second alternative of reinforcement by columns prevails when the rigid stratum is located a high depth (equals or exceeds 30 m). To proceed for the design in such soil conditions it is worth noticing, as first step, to estimate the depth on which the loaded foundation will induce non-negligible settlement as explained in Figure 5 (Bouassida & Hazzar, 2015). Beyond the settlement depth H_{sett}, induced vertical stress by the loaded foundation are negligible, hence induced settlement are almost zero at higher depth. In other terms, there is no need to extend the length of reinforcing columns beyond depth equals to H_{sett}. Therefore, the maximum length of floating columns equals to H_{sett}.

In addition to the determination of optimized area ratio explained in the above, the design of foundations on soil reinforced by floating columns involves, in second step, the optimization of columns’ length. Indeed, the length of floating columns might be lesser than Hs depending on the agreed allowable settlement of unreinforced layers located underneath the reinforced soil over depth H_c that corresponds to the length of columns.

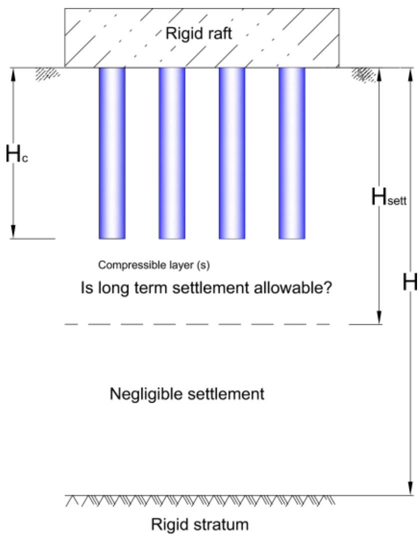

Figure 5 Reinforcement by floating columns

Based on the suggested methodology of design (Bouassida & Carter, 2014), the verification of bearing capacity (first step of the design) is carried out identically to the end-bearing columns reinforcement case. The second verification is related to the settlement. Total settlement δ_{tot} of the foundation is the sum of settlement of reinforced soil, which is assumed to occur in short term conditions due to enhanced drainage of column materials like stone columns, and the settlement of unreinforced layers. Hence:

$$\delta_{tot} = \delta_{rs} + \delta_{ur} \tag{1}$$

δ_{rs} and δ_{ur} denote the settlement of reinforced soil over length H_c and the settlement of unreinforced layer(s) of thickness (H_{sett} - H_c), respectively.

Settlement of unreinforced layer(s) represents the key issue since it often occurs in compressible layer(s), therefore a consolidation problem should be solved based on allowable residual long-term settlement. The length of floating columns should be optimized in this way: Bouassida & Debats, (2017) and Bouassida & Ellouze (2018). Two case histories are presented to show up the feasibility and efficiency of reinforcement using floating columns.

3.1 Case study n°3: Oil tank foundation on homogeneous Tunis soft clay

Collected data were from the Tunisian case history investigated by Bouassida & Hazzar (2012) and Bouassida & Carter (2014). Uniform vertical load of 80 kPa is subjected, at the surface of soft ground, by the oil tank of 20 m diameter. Tables 1 and 2 summarize the properties of Tunis soft clay layer (resting on rigid stratum) of total thickness *H* = 20 m, and columns material, respectively. The admissible total short-term settlement equals to 25 cm.

Table 1. Properties of soil layers

Depth (m)	c_u (kPa)	E (kPa)	γ (kN/m³)	ν	φ (degree)	*Compression index*	*Initial void ratio*
0 – H_c	24	2000	18	0.4	0	0.6	0.9
H_c - 20	24	2000	18	0.4	0	0.6	0.9

H_c denotes the columns' length which coincides with the thickness of first sub-layer of homogeneous soft clay.

Table 2. Properties of columns material

Columns material	C_c (kPa)	E_c (kPa)	γ_c (kN/m³)	ν_c	φ_c(deg)
Stone	0	20000	20	0.33	38
Lime-cement treated soil	150	90000	22	0.33	0

Using Columns 1.01 software, the prediction of short term settlement of foundation resting on homogeneous compressible soil, of total thickness *H*, reinforced by floating columns of length H_c requires a soil profile composed of two sub-layers having the same properties of thickness H_c and (H - H_c), respectively.

After Eq (1), total settlement of oil tank is the sum of two components: first component corresponds to reinforced soil over thickness H_c and, second is for the unreinforced soil over thickness ($H – H_c$).

Consider the two reinforcement techniques using floating either stone columns or soil treated lime-cement columns. Following the methodology of design of Columns 1.01 software, it has revealed that minimum length of floating columns is 12 m in the case of lime-cement treatment and 14 m in the case of stone columns.

Figure 6 illustrates the evolution of optimized improvement area ratio, IAR_{opt}, according to predictions by Columns 1.01 software as function of length of floating columns. From this figure it is clear that predicted decrease in IAR_{opt} is much more significant with stone columns reinforcement compared to that predicted for the deep mixing treatment. Indeed, in the range H_c = 14 m to 20 m IAR_{opt} decreases from 39 % to 14 % and from 8 to 3% for stone columns and deep mixing reinforcement, respectively.

Figure 7 shows the variations of consolidation (long term) settlement, short term settlement and residual consolidation settlement of the unreinforced soil layer in function of columns length H_c. Long term settlement is predicted by Terzaghi's one dimensional consolidation theory as detailed by Bouassida & Ellouze (2018).

From Figure 7 the length of floating columns is decided for an agreed admissible residual settlement. The residual settlement becomes negligible (i.e. less than 2 cm) from H_c = 16.5 m; hence the optimized length of columns might be chosen in the range 14 to 16 m assuming that admissible residual settlement does not exceed 5 cm in unreinforced compressible layer. Note that the French method (2005) only applies for the design (viz. settlement estimation) of stone columns, therefore the settlement of reinforced soil by the deep mixing technique is estimated using the methods proposed by Balaam & Booker (1981) and Bouassida et al. (2003) which adopt the unit cell and the group of columns modelling, respectively.

In the case of stone columns reinforcement, predictions by Bouassida et al. (2003) method provide conservative design compared to predictions by the French method (2005). The same trend is observed in the case of the deep mixing method (DMM) is considered. Indeed, Figure 8 shows that Bouassida et al. (2003) method predicts more secured design in term of settlement than prediction by Balaam & Booker's (1981) method.

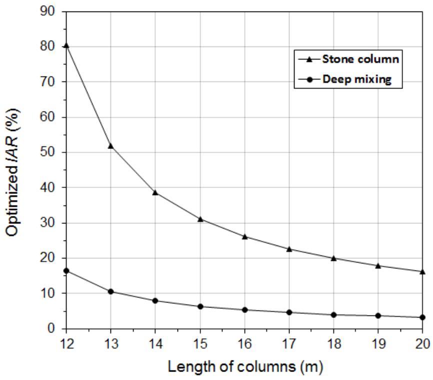

Figure 6 Variation of optimized improvement area ratio vs length of columns, case study n°3

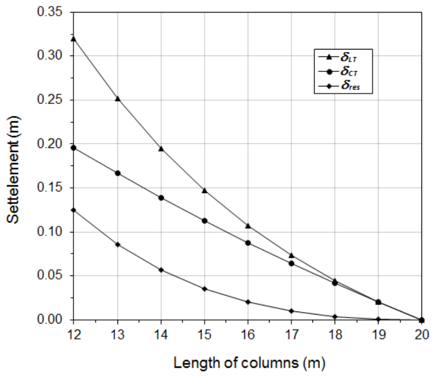

Figure 7 Variation of settlements of unreinforced soil vs length of columns, case study n°3

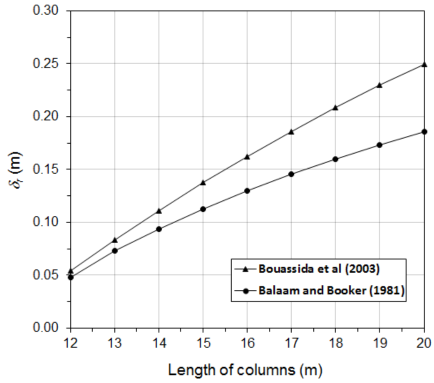

Figure 8 Estimations of settlement of reinforced soil vs length of columns, case study n°3

3.2 Case history n°4: Oil storage facility at Ghannouche (Tunisia)

The storage facility comprises two bullets of butane and five bullets of propane protected in mounded banks. Figure 9 schematizes the cross section of completely integrated embankment. Geotechnical properties of soil layers are obtained from measured CPT values during soil investigation and laboratory tests results conducted for the project. Reinforcement by stone column is suitable to reduce unallowable settlement as predicted under applied embankment load of 120 kPa. The required stability for an allowable settlement of 4 cm, over 15 years in post construction of storage facility, was agreed (Bouassida & Ellouze, 2018). Hence, significant reduction of settlement associated to the prescribed margin of security has led to the installation of floating stone columns of 11 m length, embedded in medium sand layer. Stone columns with 0.9 m in diameter were installed in triangular pattern of 1.9 x 2.2 m with IAR = 16%.

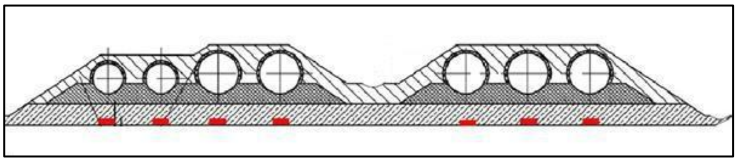

Figure 9 Cross section of whole integrated embankment

Table 3 summarizes the predictions of linear elastic settlement obtained by Columns 1.01 software for the unreinforced soil and the reinforced soil, Bouassida and Hazzar (2012). Table 3 shows quite similar predictions of total settlement by the French method (2005) and Balaam and Booker's (1981) one. Although these two methods do not take account of the improvement of the initial soil, settlement reduction closes one third by the installation of floating stone columns. Further, the use of Columns 1.01 software has confirmed that the optimized IAR, which verifies the allowable settlement of 4 cm, is 15.39 %. This prediction is close to the practiced reinforcement for the project that was 16%.

Table 3. Predictions of linear elastic settlement of embankment on reinforced soil (Bouassida, 2016a)

Layers	Thickness (m)	Settlement of unreinforced soil (cm)	Settlement of reinforced soil (cm)	
			Balaam & Booker (1981)	French method (2005)
Gypsums sand	2.5	0.5	0.26	0.25
Silt sand	6.5	6.83	1.34	1.53
Medium cemented sand (1)	5.5	0.54	0.37	0.41
Medium cemented sand (2)	7.5	3.58	1.18	1.35
Compacted fine sand	6.0	0.41	0.41	0.41

Numerical simulation of embankment behavior was carried out by Plaxis 2D software. Built plane strain model comprises a 6 m height embankment founded on the soil profile shown in Figure 10. After project data, 46 stone columns were installed along the horizontal direction, with axis to axis spacing of 1.9 m, and 30 stone columns were installed, along the perpendicular direction, with axis to axis spacing by 2.2 m, over 64 m length. The group of stone columns is modelled by a group of equivalent trenches to simulate the behavior of reinforced ground in plane strain condition, (Klai et al., 2015). Then, the equivalent thickness of a trench, b_{tr}, is determined from Eq. (2):

$$b_{tr} = \frac{30}{64}\pi a^2 \tag{2}$$

"a" denotes stone column's radius

Forty-one trenches of stone material are considered in the numerical model with dimensions: thickness: b_{tr} = 0.3 m; length: H_c = 11 m; spacing between edges of trenches: s' = 1.9 m (Klai et al., 2015). The behavior of soil layers is described by the elastic perfect plastic Mohr-Coulomb constitutive law with parameters given in Table 4 (Bouassida, 2016a). Adopted characteristics of column material are: γ_c = 20 kN/m^3, ν_c = 0.33, E_c = 60,000 kPa; φ_c = 40°; C_c = 0.005 kPa.

Table 4. Geometrical parameters of soil layers and embankment material

Layers	Height / Thickness [m]	Young Modulus [MPa]	Cohesion [kPa]	Friction angle [°]	Total unit weight [kN/ m^3]
Backfill material	6	10	1	30	20
Fine sand	2.5	30	5	30	19
Soft silt clay	6.5	5.7	2	24	18
Firm clay	5.5	60	2	24	19
Silt clay 1	7.5	12	15	10	18
Stiff clay 2	6	80	2	24	20

The numerical simulation of embankment with staged construction comprises four phases. The first phase consists of 30 days consolidation analysis that occurs upon the installation of stone columns within the compressible layers. Then, a partial horizontal consolidation is triggered that dissipates the induced excess pore pressure and leads to uniform consolidation settlement within the compressible layers. The second and third phases of numerical staged construction also consist of consolidation analysis which corresponds to loadings applied upon the execution of first and second embankment layers, respectively. A consolidation analysis is run for each loading embankment layer during 120 days and 270 days, respectively.

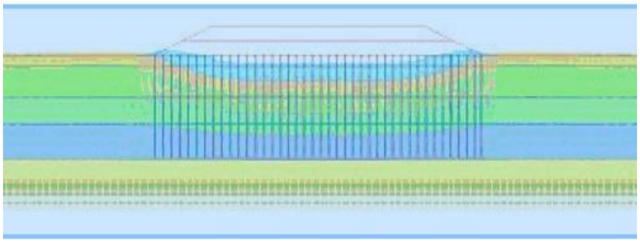

Figure 10 Geometry of numerical plane strain modelling of reinforced soil

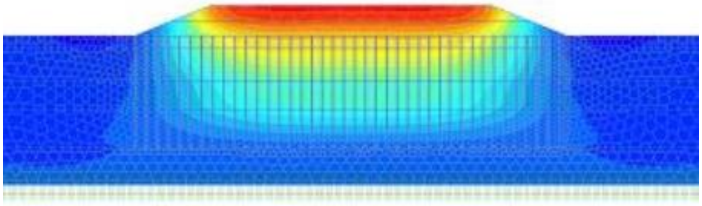

Figure 11 Contours of vertical displacements of the embankment facility on reinforced soil by stone columns subjected to a uniform load of 120 kPa.

Figure 11 shows the contours of vertical displacement with maximum value of settlement equals 8 cm at upper crest of embankment facility. Whilst, at the surface of reinforced soil, the predicted settlement is almost uniform of value 6 cm over the width of upper crest beneath the embankment. Consolidation settlement of magnitude 6.5 cm was predicted to occur in four years.

The follow up of behavior of storage facility built on reinforced ground by floating stone columns was performed by means of data acquisition unit connecting the pressure sensors, to record the evolution of settlements, located at the surface of reinforced ground (Bouassida, 2016a).

The first measured settlements induced by the acquisition unit data occurred in post construction of the backfill, and, then, stabilized when the data acquisition measurements started.

The evolution of measured settlement in function of time at profile PR02 are plotted in Figure 12. The recorded settlement after the installation of the first backfill layer varied between 1.0 and 1.7 cm and, then, were stabilized after a period of 30 days. After the completion of the entire embankment the magnitude of measured settlements was less than 3.0 cm. Based on this observation it is confirmed that the stone columns reinforcement experienced at Gannouche' site fulfilled the requirement of admissible consolidation settlement that was less than 3.5 cm.

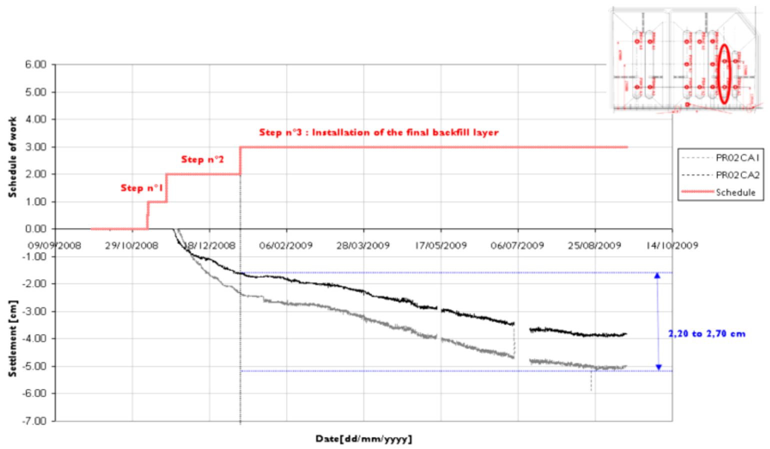

Figure 12 Evolution of measured settlement vs. time at location PR02 (Bouassida, 2016a)

The last phase of numerical staged construction also included consolidation analysis which corresponds to the final height of embankment. This phase simulates the long-term behavior fifteen years after the construction of storage facility. It is noted during the progress of stage construction of embankment, the settlement significantly increases in different locations and, then, it becomes almost uniform within the allowable limit of settlement that is 4 cm. This long-term settlement corresponds to the induced deformation within unreinforced sub-layers. After Bouassida & Hazzar (2015), the settlement of reinforced layer which depends on the length of columns, is accelerated by the drained columns' material, hence it is completed at the end of embankment construction.

Investigation of Ghannouche case history well demonstrated the usefulness of floating stone columns reinforcement as no residual consolidation settlement, occurred in the unreinforced sub-layers.

It is, then, concluded that the design of foundation of bullets of butane and propane integrated into an embankment on compressible layers reinforced by stone columns was successful. Indeed, this design permitted to comply with the allowable settlement of the foundation over fifteen years as predicted by the numerical computations. Those predictions revealed in acceptable agreement with the measured settlement that remained under 4 cm over 15 years.

4. Concluding remarks

This paper addressed the optimization of design of foundations built on soil reinforced by columns. Two reinforcement options were studied; first, for end-bearing columns, and, second, for floating columns. On the basis of recent methodology of design considering the group of columns modelling and combining verifications of BC and settlement, four case histories were investigated. Main findings from the obtained results led to the following insights.

1. In the case of end-bearing columns, based on allowable settlement of reinforced soil, the unique optimization is restricted to the IAR that can be predicted for two cases. First case, when the properties of initial soil are not affected by the installed columns, and the second case is concerned with the improvement of initial soil characteristics, like for the stone columns technique. Analysis of oil tank case history well illustrated that recent methodology of design enables to significantly reduce the IAR, compared to existing methods. Further, recorded settlements permitted to estimate the rate of improved Young modulus of loose silt sand from which another gain on IAR is potential.
2. Simulation of stone columns installation by lateral expansion was implemented by Plaxis 2D software. The use of composite cell model and reduced group of stone columns for two case histories showed up how the Young modulus of soft clay is enhanced after running horizontal consolidation implemented by the numerical “dummy material” procedure. The extent of improved zone in soft clay was estimated from which the IAR can be optimized.
3. The behavior of oil tank case study on Tunis soft clay layer of 20 m thickness reinforced by floating columns was analyzed. For prescribed allowable short settlement a minimum length (equal to 12 m) of floating columns is identified. Further, for prescribed residual (long-term) settlement of 3 cm it was proven that reinforcement by floating stone columns of length 15.5 m well complies with tank stability.
4. Fourth case history was dedicated to the reinforcement by floating stone columns of compressible layers at Ghannouche site (Tunisia). Stage construction of storage facility, comprising two bullets of butane and five bullets of propane protected in mounded banks, was simulated by Plaxis software in four phases. Using an equivalent 2D modelling of reinforced ground by floating columns of length 11 m the study of behavior of storage facility showed up that the prescribed residual settlement, occurring after the end of stage construction, did not exceed 3.5 cm as observed from recorded settlements. This prediction fulfilled the required value of residual settlement equals to 4 cm over fifteen years.

   Throughout investigated case histories it is concluded that optimizing the design of foundations on soils reinforced by columns is necessary to provide cost-effective ground improvement solutions, however the related techniques are considered cost-effective when compared, for instance, to the classical pile foundations.

References

Balaam, N.P. and Booker, J.R. (1981). Analysis of rigid rafts supported by granular piles. Int. J. of Num. & Analyt. Meth. in Geomech., 5(4), pp. 379-403.

Bouassida, M and Ellouze, S. (2018). Optimized design of foundations on soil reinforced by floating columns. Volume2, Issue2-3 Special Issue: XVI DECGE Proceedings of the 16th Danube - European Conference on Geotechnical Engineering June 2018. pp. 165-176.

Bouassida M., Klai M., Tabchouche S., Mellas M. (2017). Comparison of numerical analyses of behaviour of column-reinforced foundations, Geotechnical Engineering, 48(3) pp. 118-122.

Bouassida M. & Debats JM. (2017). A highlight on stability of road embankments on soil reinforced by floating stone columns: a Tunisian case study. Proc. 7th Geotechnical Engineering Symposium. Istanbul 22-23-24 November 2017, (1) pp. 13-23.

Bouassida, M (2016a). Design of Column-Reinforced Foundations. J. Ross Publishing (FL, USA), September. 224P.

Bouassida, M. (2016b). Rational design of foundations on soil reinforced by columns Innov. Infrastruct. Solut. 1: 38. doi:10.1007/s41062-016-0038-3. http://rdcu.be/no0r

Bouassida, M, and Hazzar L. (2015). Performance of soft clays reinforced by floating columns. Book “Ground Improvement Cases Histories, Embankments with Special Reference to Consolidation and Other Physical Methods. Edits Indraratna et al, Chap 16. Part Two: Sands and Gravel Piles, Stone Columns and Other Rigid Inclusions. Butterworth Heinemann publications. Elsevier, pp. 433-449.

Bouassida, M. and Carter, J. P. (2014). Optimization of Design of Column-reinforced Foundations. Int. J. Geomech., Volume 14, Issue 6.

Bouassida, M, and Hazzar L. (2012). Novel tool for optimized design of reinforced soils by columns. Ground Improvement:

Proc. ICE, London 165, Issue 1, pp. 31 –40.

Bouassida, M, Jellali B. & Porbaha, A. (2009). Limit Analysis of Rigid Foundations on Floating Columns. International Journal of Geomechanics, ASCE. Vol. 9, n°3 May-June, pp. 89-101.

Bouassida, M, Guetif Z., de Buhan P. & Dormieux L., (2003). Estimation par une approche variationnelle du tassement d'un sol renforcé par colonnes. *Revue Française de Géotechnique*. n ° 102, pp. 21-29.

Debats, J.M., Savasta, P. and Gambin, M.P., (1999). Vibro-replacement and static pre-loading of fine-grained granular soils: comparison and importance of in-situ control testing methods (in French) 12th Europ Conf. Soil Mech. & Geotech. Eng. Amsterdam, Barends et al Eds, (3), pp. 1761-1764.

Debats, J. M., Guetif, Z. and Bouassida; M. and (2003). Soft soil improvement due to vibrocompacted columns installation. Proc. International Workshop on Geotechnics of soft soils. Theory and practice September 17-19, Noordwijkerhout (Netherlands). Vermeer et al Eds, pp. 551-556.

Ellouze, S., Bouassida, M., Ben Salem, Z. and Znaidi, MN (2017). Numerical Analysis of the Installation Effects on the Behavior of Soft Clay Improved by Stone Columns. Geomechanics and Geoengineering: An International Journal. Volume 12, Issue 2.

Ellouze S., and Bouassida M. (2009). Prediction of the settlement of reinforced soft soil clay by a group of stone columns. Proc. 2nd Int. Conf. New Develop. in SMGE. Edit. Atalar et al. 28-30 May NEU Nicosia. pp. 182–187.

Fattah, M.Y. , Al-Neami, M.A., & Al-Suhaily, A.S. (2017). Estimation of bearing capacity of floating group of stone columns. Eng. Sc. and Tech., an International Journal. Vol. 20, (3), pp. 1166-1172.

French Method (2005). Recommandations sur la conception, le calcul, l'exécution et le contrôle des colonnes ballastées sous bâtiments et ouvrages sensibles au tassement. *Revue Française de Géotechnique*, 2ème trimestre, 111, pp. 3-16.

Frikha, W, Bouassida, M. and Canou, J. (2013). Observed behaviour of laterally expanded stone column in soft soil. Geotech. Geol. Eng. J., 31 (2), pp. 739-752.

Guetif, Z., Bouassida; M. and Debats, J. M. (2007). Improved Soft Clay Characteristics Due to Stone Column Installation. *Computers and Geotechnics*. Vol 34, n°2; pp. 104-111.

Klai, M., Bouassida, M. & Tabchouche S (2015). Numerical modelling of Tunis soft clay. Geotechnical Engineering Journal of the SEAGS & AGSSEA Vol. 46 No. 4 December, pp. 87-95.

Naama Engineering & Consulting (2001). Geotechnical report of project "Damiette LNG tanks", Vibroflotation Europe.

Ng, K.S. & Tan, S.A. (2014). Design and analyses of floating stone columns (2014). Soils and Foundations, Vol 54, (3), pp. 478-487.

Shahu, J.T. & Reddy, Y.R. (2014). Estimating long-term settlement of floating stone column groups. Canadian Geotechnical Journal. doi/10.1139/cgj-2012-0477.

Tabchouche S., Bouassida M. and Mellas M (2018). Behavior of foundation on end-bearing stone columns group reinforced soil. Accepted in Geotechnical Engineering Journal of the SEAGS & AGSSEA.

Abbreviations

BC: bearing capacity, IAR: improvement area ratio, SC: stone column(s), HSM: hardening soil model

◆ A Brief CV of Prof. Mounir Bouassida

M. Bouassida is a professor at the National Engineering School of Tunis of the University of Tunis El Manar where he earned his B.S., M.S., Ph.D., and doctorate of sciences in civil engineering. He is the director of the Geotechnical Engineering Research Laboratory, focusing on soil improvement techniques and behavior of soft clays. Dr Bouassida elaborated a novel methodology for the design of foundations on reinforced soil by columns. He was awarded the 2006 Prakash Prize for Excellence in the practice of geotechnical engineering. Dr Bouassida is the advisor of consulting office, SIMPRO he founded in 2008. He is a co-developer of the software Columns 1.01 used for the design of column-reinforced foundations. Prof. Bouassida held the office of the vice president of ISSMGE for Africa (2005–2009). He is an appointed member of the ISSMGE (2017-2021).