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A NUMERICAL STUDY ON SOIL IMPROVEMENT USING THE VIBRO-STONE COLUMNS TECHNIQUE "CASE OF BOUREGREG VALLEY"

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ABSTRACT

This paper deals with the improvement of soft soils generated by the installation of stone columns under the engineering structures of the "Bouregreg valley", the study falls within the sustainable development of the valley. At the site level, the presence of muddy low consistent formations contributes to phenomena of settlement and liquefaction. To overcome these defects, stone columns are used as a soil improvement technique to reduce settlement and to increase the foundations' bearing capacity on soft clay soil [12]. The installation of the stone columns influences the surrounding soil, because under the action of compaction, the surrounding soil bear lateral expansion, as a result, horizontal stresses increase. Numerical modelling is a simple and effective method to approach the real behaviour of soils. It allows settlement analysis, lateral deformation, vertical and horizontal stresses. It also evaluates the value of the lateral pressure coefficient and the variation in the structure. The proposed study is based on analytical and numerical approaches [21] to determine the treatment of compressible soil by stone columns technique. The aim of this paper is to study the numerical simulation's results. The properties of the soft soil correspond to "Bouregreg valley"- soil. This paper is structured as follows: the first part provides the soil conditions and the parameters related to columns and the second part presents 3D finite element analyses that study the stone columns' performance and lateral pressure coefficient variation. These 3D analyses aim to clarify the most important parameters, the influence of the constitutive models and the column geometry.

Key words: Soft Soils, Settlement, Stone Columns, Lateral Expansion and Numerical Simulations.

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1. INTRODUCTION

The "Bouregreg Valley" stretches over 6000 hectares, between the cities of Rabat and Salé, from the Atlantic Ocean to the dam Sidi Mohammed Benabdallah. The valley is distinguished by the high quality of its urban and rural landscapes [16-42]. This is both the lung of the metropolitan area of Rabat-Salé and the central space that brings major regional green areas into a coherent whole.

In ecological terms, the fauna and flora of the valley are very rich in species and reflect a wide biodiversity; moreover, the surrounding humidity favours the development of vegetation all year long [16].

Particular interest is given to the preservation of the ecosystem, the protection and the development of the natural landscape; the priority is given to depolluting the valley and the river, the rehabilitation of the natural site as a whole [43].

The implementation of various structures is provided for this purpose. The ground in the valley is manifested by weak mechanical characteristics; deformation under significant loads and low bearing capacity [30]; which poses a real challenge for the geotechnical to overcome these defects. Various soil-building techniques have been developed and applied over the last years ; stone columns are used as a soil-improvement technique to reduce settlement and to increase the bearing capacity of foundations on soft clay soil, the benefits arise from the fact that there is a partial replacement of the compressible soil by a more competent material (compacted stone aggregates). Moreover the stone columns are highly permeable and act as vertical drains facilitating consolidation of the soft soil improving the performance of the foundation. They lead in particular to the general stability of embankments and the mitigation of the liquefaction phenomena. Therefore, they facilitate the soft soil's consolidation and improve the foundation's performance. [19-11-27-4-45]

The majority of analytical methods pertain to primary settlement only [34-35-36]. Current works on modeling, testing, and analysis of compressible soil reinforced with stone columns were reported by McCabe et al, 2009, Mokhtari and Kalantari, 2012; Najjar, 2013; Balaam and Booker,1981; used the concept of unit cell to study the capacity of single stone column. [24-26-28-29-2]

Sexton et al, 2013; demonstrate that some recent analytical methods are successful. [39-9-36-18-8-10] These analytical methods can be implemented mathematically using a unit cell model. However, unit cell models cannot capture the behavior of peripheral group columns beneath footings.

The numerical modeling [23] of a group of stone columns has predominantly been the focus of several studies: Shahu and reddy, 2011; Wehr, 1999; and Muir Wood et al, 2000; investigated the performance of groups of stone columns using finite-element analysis. [40-27-43-44-45]

This paper aims to study the numerical simulation results, also, the effect of stone column installation and the influence of lateral expansion, then the investigation of the treatment of compressible soil by stone columns technique. The properties of the compressible soil correspond to "Bouregreg valley"- soil. The modeling was done using the 3D finite element method.

2. DESCRIPTION OF THE STUDY AREA AND THE SITE CHARACTERIZATION

Bouregreg valley is located on the Atlantic coast, north of Casablanca. In geographical coordinates, the valley is about 34°01 North Latitude and 6°49West Longitude. It is relatively encased and the slopes present risks of instability. It is the only major accident of the the relief in the agglomeration site. It develops between the plates Youssoufia Akreuch in the West and Kariat Hssaine in the east, where the coastal river describes ample meanders. It tightens near the mouth and at the confluence with the river Akreuch. The dam Sidi Mohammed Ben Abdellah is built at the exit of the gorge.

The valley represents an alluvial plain with a very pronounced topography, and width between 0.3 km to 3 km. This is at the Kasbat Abi Raqraq, that this reaches its maximum width. The topography is characterized essentially by the slopes whose gradiant is generally steep. Their height reaches approximately 160 m high at the SMBA dam. And twenty meters in Laval near the mouth. The slopes are also incised by seasonal watercourses that flow into the valley.

The study area is situated at 4 km from Atlantic Ocean, at thirteen meters upstream from the old bridge Moulay Youssef, next Fida Bridge.

Figure 1 Geographical location of the study area and samples for laboratory tests.

A campaign for recognition was implemented at the site of the "Bouregreg valley". Core drilling, with removal intact and reshaped samples (Figure 1) allowed making laboratory tests (identification and characterization of soils), and establishing a detailed section of land. Pressumeter tests were realized to determine soil pressumeter characteristics.

Table 1 Characteristics of the "Bouregreg valley" soil

Soil Layers	Depth (m)	γ (kN /m3)	E (kPa)	Φ (°)	c(kPa)
Silty clay	2	18	2295	15	25
Clay	6.5	18	2585	15	25
Clay with sandy layers	10.5	19	18334	23	0.5

The soil at "Bouregreg valley" consists of silty clay about 2 m thick, which is underlain by about 8.5 m of soft clay; between 6.5 and 10.5 m, the clay layer has some occasional thin sandy layers. Below a depth of 10.5 m the soil gets stiffer (consistent sand) (Table 1).

In the simulations the columns were assumed to reach this rigid soil at 10.5m depth. The ground water level is at the surface (γw=10 kN/m3). We are interested in the layers of low geotechnical properties, whose characteristics are determined in Table 1.

We used the following formulas for the calculation of Young's modulus:

$$E = E_{oed} \frac{(1-2\nu)(1+\nu)}{1-\nu} \quad (1)$$

With ν : Poisson's ratio

E_{oed} : Œdometric modulus calculated based on the pressuremeter modulus by the relationship

$$E_{oed} = \frac{E_M}{\alpha} \quad (2)$$

In which α is a rheological coefficient that depends on the type of soil and the limit pressure.

Stone columns: 10.5 m deep with an average diameter of 0.8 m and a spacing of 1.5 m.

3. REFERENCE CASES

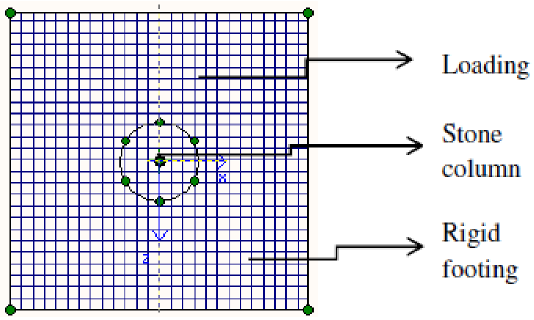

Figure 2: Numerical model (Plaxis 3DF) of an isolated stone column

In the first case (Figure 2); the reference consists of only one stone column under the center of a square rigid footing. The footing width, B, is 1.5 m (B=s) and the column diameter is equal to 0.8 m (dc=0.8 m). The column is considered to reach a rigid substratum at 10.5m depth. So, the column is end-bearing (L/H=1) and has length of L=10.5m. The column is modeled in the center of a large soil mass (36 mx36 mx10.5 m)(Figure 2) to avoid the edge effect, the footing of 0.5 m thickness, is considered as a material with properties of concrete :

γ =24 kN /m3, E=3.107 kPa and ν=0.15.

In accordance with standard practice for numerical modeling of stone columns, column-soil interface elements are not used [40].

A uniform vertical pressure of P=100 kPa is applied on the rigid square footing.

3.1. Layers effects

The soil profile adopted for the "Bouregreg valley" test site is modified to investigate the effect of the compressible clay and the other layers (Figure3). The settlement's performance for various column arrangements is investigated for the various profiles shown in Figure 3.

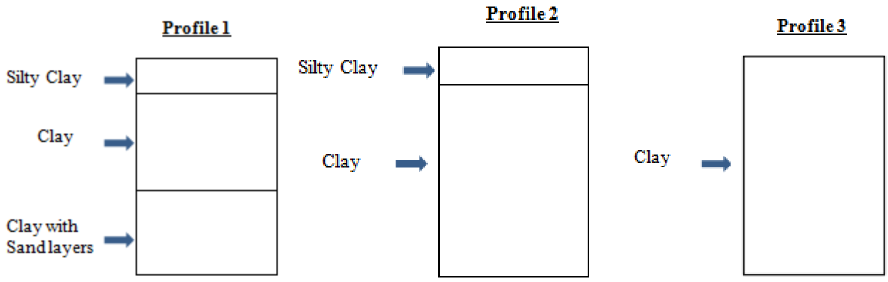

Figure 3 Various profiles adopted to investigate layers effect.

The settlement's performance of these profiles is evaluated for an applied pressure varying between 100 kPa and 300 kPa. Due to soil heterogeneity of the "Bouregreg valley", various profiles were considered. This allows us to study the effect of soil layers.

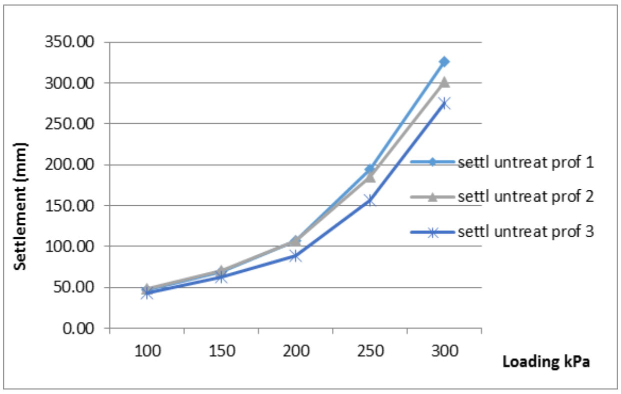

Figure 4 Settlement of untreated soil for various profiles.

The graphs (Figure 4) illustrate for different values of loading, the settlement of three adopted profiles shown in Figure 3

The graphs (Figure 4) show that:

- The settlement of profiles 1 and 2 is higher than profile 3; this is due to the presence of the silty clay layer which is a compressible soil.
- Profile 1 and profile 2 have almost the same graph for a loading less than 250 kPa.
- For small loads settlement is almost the same for all the three profiles, so for reasons of simplification, it may adopt the profiles 2 and profile 3 for small loads.

3.2. Meshing and boundaries

Plaxis 3DF generate the finite element mesh using a triangulation procedure, but global and local mesh refinements may be defined to ensure a good quality of the mesh, in this way a 3D mesh, composed of 15-noded wedge isoparametric elements is formed, refining the mesh in the area of interest (footing and column) and using a coarse mesh in the far field.

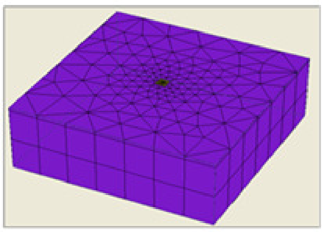

Figure 5 Typical mesh for finite element modelling, (profile 3)

Figure 5 show for the profile 3 the typical mesh adopted for finite element simulation, with locally refined mesh in the area of interest. The lateral boundaries allow vertical movement but restrict radial movement; therefore, it is necessary to position them at a sufficient distance from the footing so that boundaries conditions do not influence the results Killeen (2012).

Along the bottom of the soil mass both radial deformation and settlement are restricted (Full fixity is assigned at the base of the geometry). [21]

Many authors have declined to use interface elements at the boundary between the granular column material and the in situ soil [1-13-22-40], the stone columns become tightly interlocked with the surrounding soil due to the lateral displacement [24-25]; Perfect adhesion is assumed at the column–soil interface.

3.3. Constitutive models

The use of the finite element analysis has become widespread in geotechnical practice an efficient mean of optimizing engineering tasks; however the quality of any prediction depends on the adequate model being adopted in the study.

The choice of a constitutive model [42] depends on many factors but, in general, it is related to the type of analysis that the user intends to perform. Three sets of calculations were made using different material models on soils: the linear-elastic model, the Mohr-Coulomb model and the Hardening Soil model.

3.3.1. Mohr coulomb model

The Mohr coulomb model idealizes soil as an elastic perfectly plastic material. The behavior of soil before failure is approximated by Hooke's law of elasticity; the failure of soil is based upon the Mohr-coulomb criterion which is defined by two parameters, angle of internal friction and cohesion.

3.3.2. Hardening soil model

The Hardening soil model is an advanced elasto-plastic constitutive model [33] which can be used to simulate the behavior of both the granular column material and the treated soft clay soil; it's an extension of the hyperbolic model developed by Duncan and Chang (1970) [14]. The model supersedes the hyperbolic model as it's based on the theory of plasticity rather than elasticity, includes soil dilatancy and introduces a yield cap. It accounts for both shear and volumetric hardening, thus capturing irreversible strains caused by deviatoric and compression loadings, respectively.[37].

The hardening soil model was considered appropriate for the granular column material [39]. The value of friction angle ϕ=45° has been selected while the dilatancy angle was calculated as $\psi=\phi$- 30° (Bolton, 1986). [5] A very small value of the cohesion (c=0.1 kPa) is used to avoid numerical instabilities. A value of m= 0.3 has been used as the power for stress-level dependency of the stiffness. The oedometric modulus Eoedref= 23.3 MPa was assumed equal to the secant modulus E50 reffor a reference pressure of pref = 100kPa, and the unload-reload modulus Eurref was taken as 3E50ref = 70 MPa proposed by Brinkgreve § Broere (2006) [6]. A poisson's ratio of νur= 0.2.

For the soft soil: the power is taken equal to m=1 as recommended by Brinkgreve et al, the reference pressures in the soil and column materials are identical.

4. PARAMETRIC STUDIES (CASE OF AN ISOLATED COLUMN)

This section analyzes the settlement performance of an isolated column, which is determined by the settlement improvement factor, β.

The parametric studies were carried out varying several properties: layers and the area ratio, friction angle of column material and constitutive models

During stone column installation, the vibrator displaces the surrounding soil laterally; therefore its characteristics are altered. These effects are nowadays among the most important concerns for stone columns technique.

4.1. Layers and the area ratio

This parametric study aims to show the effects of different layers of the soil in the site of "Bouregreg Valley" after treatment by stone columns method. Considering an isolated column and the three adopted profiles: For the stone columns material properties; we adopt the Mohr coulomb constitutive model and an angle of internal friction about 45°. So the settlement improvement factor for an applied pressure of Papp= 100 kPa is determined in Figure 6.

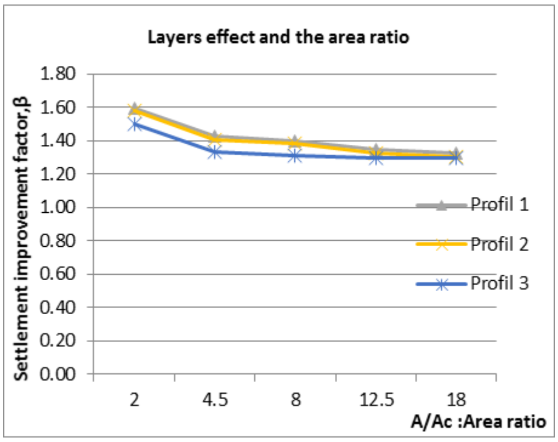

Figure 6 Settlement improvement for various profiles and area ratio for an isolated column

The "Figure 6" describes the variation of the settlement improvement factor for the three profiles according to the area ratio.

The examination of the graphs (Figure 6) leads to observe:

- The settlement improvement factor decreases with the increase of the area ratio for all the three profiles.
- For profile 1: the value of β varies from 1.32 to 1.59, for profile 2: the value of β varies from 1.30 to 1.58, and for profile 3: the value of β varies from 1.29 to 1.50.
- Profile 1 and profile 2 have almost the same graph for 2 <A/Ac<18.
- So for this case and for the sake of simplicity, it may adopt the profile 2 (for this section).

4.2. Friction angle of column material

To examine the influence of the internal friction angle of column material and the area ratio for an isolated column, we adopt profile 2 and the Mohr coulomb constitutive model for the column material.

The graphs (Figure 7) illustrate for different values of A/Ac, the settlement improvement factor, β for different values of Φ (35°/40°/45°):

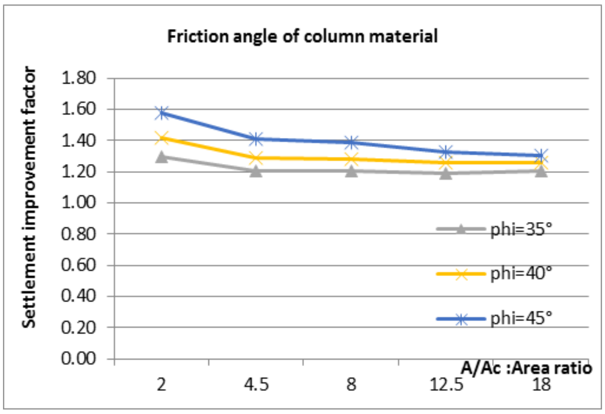

Figure 7 The influence of internal friction angle of the isolated column and the area ratio

- We observe that the increasing in the internal friction angle of the ballast increases the settlement reduction.
- For A/Ac=2 (low value of area ratio); β varies from 1.30 (Φ =35°) to 1.58 (Φ =45°), whereas For A/Ac=18 (high value of area ratio); β varies from 1.20 (Φ =35°) to 1.30 (Φ =45°).
- The settlement increases when A/Ac increases for all values of the internal friction angle of the ballast.
- The graphs approach for high values of A/Ac, so the increasing of ballast friction angle has negligible effects for high values of area ratio.

4.3. Constitutive models of column material

To examine the influence of the constitutive models of column material and the area ratio for an isolated column, we adopt profile 2, the Mohr coulomb model for the soil and ϕ=45° for the column (MC and HS).

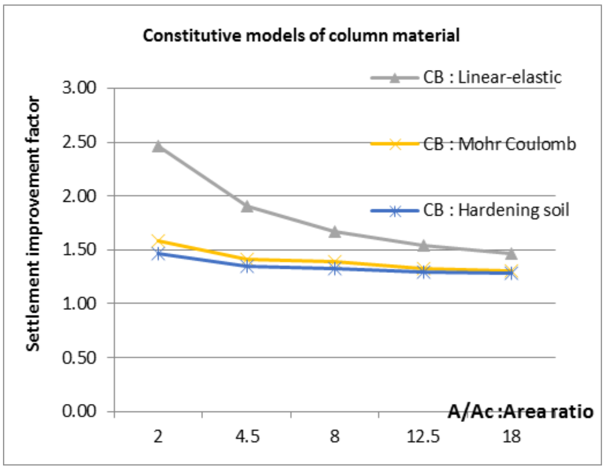

Figure 8 Settlement improvement for different constitutive models of the column material

The graphs (Figure 8) illustrate for different values of A/Ac, the settlement improvement factor, β for the behavior rules of column material (Mohr coulomb, Hardening soil and linear elastic models):

- The settlement improvement factor decreases with increasing A/Ac.
- While varying A/Ac from 2 to 18; β varies from 2.46 to 1.46 (for linear elastic model), from 1.46 to 1.28 (for Hardening soil model) and from 1.58 to 1.30 (for Mohr coulomb model).

- The two constitutive models for column material (Mohr coulomb and Hardening soil) reach approximately the same graph.
- The elastic solutions overestimate the settlement reduction, especially that realistic values are used.

4.4. The influence of lateral expansion in the installation phase of the column

The main effect is due to expansion of the cylindrical cavity created by the vibrator, and under the effect of the ballast compaction, so the surrounding soil undergoes a lateral expansion as well as an increase in the horizontal stresses N T.Nguyen (2008).

This lateral expansion depends on the tool used for the realization of the columns and the Young's modulus of the soil. We will then model numerically (3D) the stone columns taking into consideration the effect of their placement. By adopting different values of the radial expansion (Exp) of a column (0%, 4%, 8%, 12% and 16%). The column is assumed to be governed by the Mohr-Coulomb behavior law.

The objective of this part is to determine the variation of the lateral earth pressure coefficient for soil K (ratio of the horizontal stress "σ'h" to the vertical stress "σ'v") and the mean effective stress P ' under the effect of lateral expansion (which varies from 0% to 16%);

Table 2 The horizontal, vertical and mean effective stresses in kN / m2 at the edge of the column for the various lateral expansions

EXP	σ'h(kPa)	σ'v(kPa)	K	P'(kPa)
0%	146,36	292,56	0,50	195,06
4%	903,01	300,09	3,01	482,49
8%	1700	388,48	4,38	791,45
12%	2230	486,82	4,58	1140,00
16%	2360	562,72	4,19	1330,00

Table 3 The horizontal, vertical and mean effective stresses in kN / m2 at the distance Re (radius of equivalence) from the center of the column, for the various lateral expansions

EXP	σ'h(kPa)	σ'v(kPa)	K	P'(kPa)
0%	146,36	292,56	0,50	195,06
4%	349,12	293,13	1,19	252,99
8%	553,35	353,64	1,56	427,53
12%	694,71	426,98	1,63	585,92
16%	798,96	510,27	1,57	725,26

Table 4 Ratios of the horizontal and mean effective stresses for the various lateral expansions

	At the edge of the column		At the distance Re from the center C	
EXP	K/K0	P'/P0	K/K0	P'/P0
0%	1,00	1,00	1,00	1,00
4%	6,01	2,47	2,38	1,30
8%	8,75	4,06	3,13	2,19
12%	9,16	5,84	3,25	3,00
16%	8,38	6,82	3,13	3,72

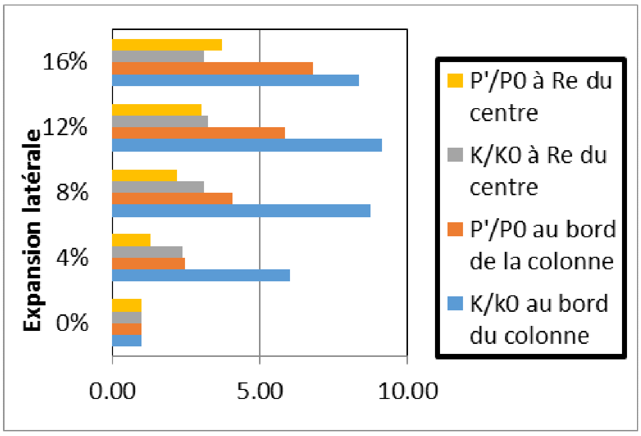

Figure 9 The effective horizontal and average stresses ratios at the column edge and the distance

For that reason we take points at the edge of the column "Table 2 ", and points at the limit of the column's influence" Table 3 " (point distant from the center of the column by the distance Re), for the different values of The lateral expansion.

We determine in these points; the horizontal, vertical and mean effective stresses (using Plaxis 3DF software); in order to calculate the K/K0 and P'/P0 ratios (the index 0 indicates the "without expansion" case) that show their variation under the influence of the lateral expansion "Table 4".

In this case, the column length is equal to 10.5 m, the column diameter is about 0.8 m, a superposition of layers of compressible soil , Ec = 60 MPa and φc = 38 ° :

The table ("Table 4") shows the ratios of the horizontal and mean effective stresses for the various lateral expansions.

For the three tables ("Table 2", "Table 3" and "Table 4"), we denote by:

Exp: Lateral volume expansion

σ'h : horizontal effective stress

σ'v :vertical effective stress

K: The ratio of effective horizontal and vertical stresses

K0: The ratio of horizontal and vertical effective stresses for null radial expansion.

P': mean effective stresses.

P0': mean effective stresses for null radial expansion.

The table and the graph above ("Table 4" and "Figure 9") illustrate the increase in the horizontal stresses (K / K0) and the average effective stresses ratio (P '/ P'0) generated by the column radial expansion. We note that the ratios are very large at the column edge.

Anyway, the expansion induced higher values than the unit in the case of the points located in the column influence area. During the radial expansion, the horizontal stress in the soil around the column increases. Therefore, the earth's thrust coefficient K (ratio of the horizontal stress to the vertical stress) does not remain equal to its initial value, and also increases it under the column lateral expansion effect.

5. CONCLUSION

From the perspective of sustainable development, Morocco was conscious of the importance of the sustainable development, including of the" Bouregreg Valley".

The stone column behavior was studied using different approaches: Numerical modeling, parametric study concerning the case of an isolated column in the center. The comparison of these different methods helps to understand the mechanisms of functioning and interactions of stone columns vis-a-vis the various parameters characterizing the granular material "ballast" and the surrounding soil. The settlement performance of various configurations of columns beneath rigid square footing is examined in this study using the PLAXIS 3DF software.

The parametric studies concerning an isolated column were carried out varying several properties: layers, the area ratio, friction angle of column material and the constitutive models; due to the heterogeneity of the soft soil we have adopted three profiles; which allows to determine that the presence of the silty clay layer increase settlements. Properties of column material (internal friction angle, constitutive models) influence the settlement improvement, especially for low values of A/Ac, we discuss also the behavior of an isolated column by taking radial expansion into account. During the radial expansion, the horizontal stress in the soil around the column increases. Therefore, the earth’s thrust coefficient K (ratio of the horizontal stress to the vertical stress) does not remain equal to its initial value, and also increases it under the column lateral expansion effect.

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