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Numerical simulation of stone column installation using advanced elastoplastic model for soft soil

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ABSTRACT: A numerical procedure is proposed to simulate the stone column installation in a normally consolidated soft clay layer. This simulation is performed by the use of Plaxis software version 8.1. Numerical computations are conducted by implementing a hardening soil model of normally consolidated soft clay which take account of the stress-stiffness dependency. From the obtained results it has been predicted both the increase of soft clay Young modulus and the radius of the area where this improvement is occurred.

1 INTRODUCTION

Stone columns are widely used to improve weak cohesive soft soils. The columns technique is an economical solution as foundation for structures having large loading area, e.g. embankments, storage tanks (Priebe 1995)... Stone columns serve three advantages namely: increase of bearing capacity, settlement reduction, and acceleration of consolidation by providing shorter drainage paths and higher permeability of columns material.

It should be noted that the reinforcement by stone columns has been largely reported in looking mainly for the predictions of bearing capacity and settlement, while the settlement acceleration was not always the prime interest.

Focusing on predictions of settlement, a variety of either analytical or numerical methods was proposed, (Balaam & Booker 1981, Van Impe & De Beer 1983, Bouassida et al. 2003, Guetif 2004). In these contributions the settlement reduction is the consequence of a partial substitution of the native soil by a stiffer material and equivalent stiffness characteristics of the reinforced soil have been established. However it is shown from experimental data (Vautrain 1980, Sanglerat 2002, Dhouib & Blondeau 2005, Alamgir & Zaher 2001) that the stiffness of native soil is also increased after the stone column installation.

The column installation is generally modeled by pouring stone (or gravel) into pre-formed holes with prescribed radius. It should be noticed that such a type of modeling is not realistic because the installation is accompanied by a lateral expansion of column in the native soft clay (Guetif et al, 2007).

Most of the design methods (Priebe, 1995, etc.) for stone columns assume unchanged Young modules of the native soft soil E_s and of the column material E_c. However, in soft clay deposits, the stiffness is variable with depth, or equivalently, with the degree of confinement (Biarez et al. 1998, Schanz et al. 1999).

The assumption of unchanged stiffness of the improved soil shall lead to an underestimation of settlement reduction.

After field data of soil improvement projects, during the consolidation, the increase of mechanical characteristics of soft clay reinforced by stone columns was well observed (Vautrain 1980, Sanglerat 2002, Dhouib & Blondeau 2005, Alamgir & Zaher 2001). The increase of native soil stiffness appeared to be an obvious consequence of the increase of effective mean stress during the consolidation period, (Biarez et al. 1998).

This paper presents a simulation of vibrocompacted column installation performed to investigate its effect on the stiffness of native soil. For this purpose, a recent contribution revealed a significant increase of native soil stiffness by adopting Mohr Coulomb model for soft clay reinforced by vibrocompacted stone column (Guetif et al, 2007). As continuation, in this paper, a hardening soil model (HSM) which shall give a more realistic characterization of the soft clay behavior is adopted (Brinkgreve and Vermeer 1998, Schanz et al. 1999). By using such a model the increase of soil stiffness with stress level can be taken into account. But, as disadvantage, the needed time for numerical computation will be greater.

The aim of this work is, then, to predict the increase of Young modulus of a native normally consolidated soft clay reinforced by vibrocompacted stone columns, and the radius of improved zone.

First, the constitutive model is presented for normally consolidated soft clay.

Second, the simulation of column installation is presented from which the prediction of stiffness improvement is derived.

The paper ends with some conclusions and remarks related to the obtained results. An outlook on further developments is proposed.

2 BEHAVIOUR OF NORMALLY CONSOLIDATED SOFT CLAYS

This section is dedicated for analyzing the behavior of normally consolidated soft clays. In some investigations the hardening soil model (HSM) has been considered to characterize the behavior of soft clays (Schanz et al. 1999, Guetif et al. 2006). Also, the HSM was largely adopted to predict the behavior of sands.

After stress-strain curves recorded from drained triaxial tests carried out on soft clays, it is shown the consolidation pressure significantly affects the behavior in the range of small strains as well as large strains. As examples the results obtained from experiments conducted by Biarez & Hicher (1994) and Tounekti et al, 2007) illustrated a strong non-linear stiffness which depends on the stress level. This fact can not be reproduced if Mohr Coulomb behavior model is envisaged for soft clays. Meanwhile the use of HSM permits to predict the increase in stiffness as a result from effective stress consolidation, Schanz et al (1999), Brinkgreve and Vermeer (1998). Compared to Mohr Coulomb model, the implementation of an elasto-plastic HSM provides the advantage in controlling the stress-stiffness dependency for a given loading path.

The stress-strain behavior for primary loading is characterized by the stiffness modulus E_{50}, which is considered instead of initial tangent modulus E_i for small strain. For this latter the experimental determination appears more difficult. The modulus E_{50} is determined from deviatoric stress-axial strain curves recorded after drained triaxial tests. E_{50}, which corresponds to the half of the maximum shear strength, is calculated from the stress-stiffness relation (Schanz et al, 1999):

$$\boldsymbol{E}_{50} = \boldsymbol{E}_{50}^{ref}\left(\frac{\boldsymbol{\sigma}_3 + \boldsymbol{c}' \cot g\boldsymbol{\varphi}'}{\boldsymbol{\sigma}_3^{ref} + \boldsymbol{c}' \cot g\boldsymbol{\varphi}'}\right)^{\boldsymbol{m}} \quad (1)$$

c' and φ' are drained strength characteristics.
m is the degree of stress dependency, for normally consolidated soft clays it is recommended $m = 1$.

The HSM does not involve a unique relationship between the drained triaxial modulus E_{50} and the oedometric modulus E_{oed} which is determined independently from:

$$\boldsymbol{E}_{oed} = \boldsymbol{E}_{oed}^{ref}\left(\frac{\boldsymbol{\sigma}_1 + \boldsymbol{c}' \cot g\boldsymbol{\varphi}'}{\boldsymbol{\sigma}_1^{ref} + \boldsymbol{c}' \cot g\boldsymbol{\varphi}'}\right)^{\boldsymbol{m}} \quad (2)$$

Table 1. Hardening soil model parameters for soft clay.

γ kN/m^3	E_{50}^{ref} kPa	E_{ur}^{ref} kPa	E_{oed}^{ref} kPa	m	c' kPa	φ'°	ψ°	k_0	k_x m/day
18/17	2500	20000	1300	1	2	25	0	0.7	2.10^{-4}

γ = unit weight saturated/unsaturated; ψ = dilatancy angle; k_x = horizontal permeability.

For unloading and reloading stress paths, the recognized modulus is:

$$\boldsymbol{E}_{ur} = \boldsymbol{E}_{ur}^{ref}\left(\frac{\boldsymbol{\sigma}_3 + \boldsymbol{c}' \cot g\boldsymbol{\varphi}'}{\boldsymbol{\sigma}_3^{ref} + \boldsymbol{c}' \cot g\boldsymbol{\varphi}'}\right)^{\boldsymbol{m}} \quad (3)$$

E_{oed}^{ref} is determined for a referenced major principal stress $\sigma_1 = 100$ kPa.

E_{50}^{ref}, E_{ur}^{ref} are determined for a referenced minor principal stress $\sigma_3 = 100$ kPa.

More details related to the HSM constitutive law can be found in Brinkgreve and Vermeer (1998) and Schanz et al. (1999).

In order to study the influence of stone column installation on soft clay behavior parameters of the HSM are adopted in the numerical simulation (Biarez & Hicher 1994). These parameters are calibrated with experimental data from oedometric and drained triaxial tests carried out on normally consolidated clay.

Using the HSM parameters proposed in table 1 for soft clay, the loading paths of oedometer and drained triaxial tests are well reproduced (Biarez et Hicher 1994).

It was also reported that the use of HSM makes possible in reproducing other loading paths such as the pressumeter test (expansion of cylindrical cavity) (Biarez et al. (1998), Brinkgreve and Vermeer (1998), Schanz et al. (1999).

It is, then, agreed a more wide use of the HSM, for normally consolidated soft clays, permits to simulate various loading paths as those occurring in several soil mechanics in situ tests. For this reason, the implementation of HSM is intended to analyze, first, the soft clay behavior that results during and after stone column expansion and, second, the expected improvement in term of Young modulus.

3 SIMULATION OF COLUMN INSTALLATION

3.1 *Reinforced soil characteristics*

The saturated subsoil comprises a sand layer up to 5 m thickness followed by normally consolidated soft clay up to 10 m thickness overlying a rigid and impervious stratum (Fig. 1). The soft clay is reinforced by vibrocompacted stone columns with 1 m of final diameter and 2.7 m of triangular grid spacing. The characteristics of soft clay are given in table 2.

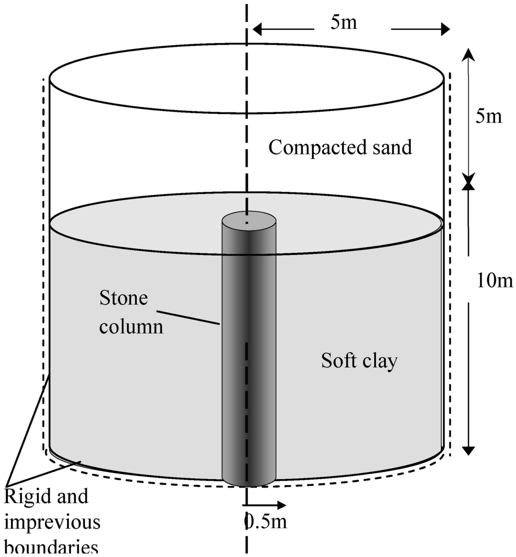

Figure 1. The composite cell model.

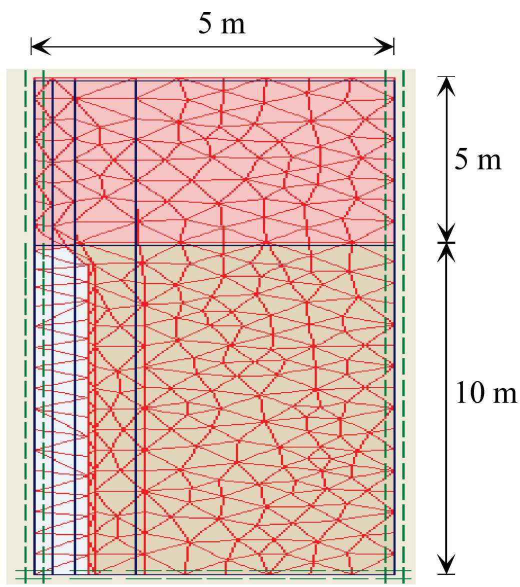

Figure 2. Deformed mesh of the composite cell model.

Table 2. Characteristics of the reinforced soil.

	γ kN/m^3	E′ kPa	c′ kPa	$\psi°$	$\varphi'°$	k m/day
Column material	20	32000	1	8	38	100
Initial sand	18	25000	1	5	35	10
Compacted sand	20	50000	1	8	38	10

Column material and sand layer are modeled as Mohr Coulomb materials which characteristics are given in Table 2.

To simulate the stone column installation a composite cell model is considered with external radius of 5 m (Fig. 1). The influence of boundary condition has been discussed in previous contributions (Debats et al. 2003, Bouassida et al. 2003b). From the latter it has been indicated that the soft clay is not influenced by the column installation beyond a radius of 5 m that is adopted for the composite cell model. It should be reminded that the installation of vibrocompacted stone column is due to the soft clay expansion from initial diameter of 0.25 m to a final diameter of 0.5 m (Guetif, 2004).

The numerical analysis is carried out by implementing an axisymmetric study with 15-noded triangular elements. The initial stresses are generated by assuming a coefficient of lateral earth stress $k_0 = 1 - \sin\varphi' = 0.69$. In this analysis the up-dated mesh option is used to take into account the large prescribed displacement especially around the interface soil-column.

The finite element mesh of composite cell is shown in Figure 2 after the installation of vibrocompacted column.

3.2 *Simulation of column installation*

The numerical procedure adopted to simulate the installation of vibro-compacted column in soft clay comprises four stages which are:

- The vibro-probe is generated by the creation of a hole of initial diameter of 0.5 m.
- The withdrawal of the vibro-probe generates a hole in which the ballast will be incorporated.
- The ballast is expanded laterally: this stage is simulated at the interface soft clay-column where a prescribed lateral displacement is applied up to a final diameter of 1 m.
- In the upper sand layer, the soil improvement is pursued by vibrocompaction until a complete withdrawal of the vibro-probe.

After the column installation, the purpose is to study the soft clay improvement resulting after a given period of consolidation (eleven months) which is assumed as taking place horizontally around the column. The deformed mesh of the composite cell after column installation is presented in Figure 2.

4 PREDICTION OF SOFT CLAY IMPROVEMENT

The expansion of vibrocompacted stone column represents the loading of the surrounding soft clay where

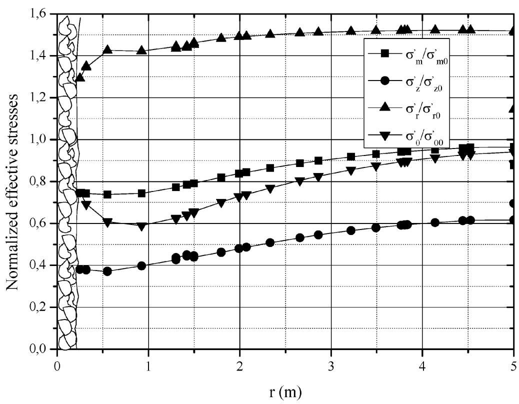

Figure 3. Normalized effective stresses distribution at mid-thickness of soft clay, before consolidation.

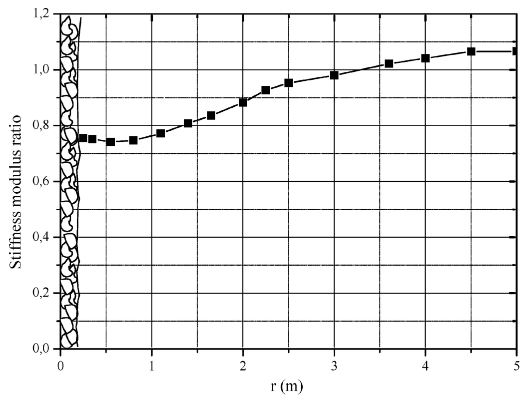

Figure 4. Stiffness modulus ratios at mid-thickness of soft clay, before consolidation.

the consolidation process takes place and the constitutive ballast plays the rule of vertical drain due to its high permeability (Table 2). Therefore excess pore pressures generated in the soft clay especially at the column's vicinity will be dissipated by radial drainage towards the column. As result, the effective state of stress in soft clay is modified from which the improvement of Young modulus will be determined from Eq (2).

4.1 *Results of numerical simulation*

The evolution of effective stress is examined at mid-thickness of the soft clay layer at the end of two phases. The first phase corresponds to the end of pouring column material which is accompanied by vibroprobe withdrawal. At this stage predicted results of numerical simulation showed up a significant excess pore pressure generated at the vicinity of the column. Contrarily, the effective mean stress distribution is slightly modified regarding that occurring before column installation (Fig. 3).

In addition the column expansion induces large plastic strains, close to soft clay-column interface, which vanish progressively when radial distance increases. Consequently, a lateral confinement is exerted by the expanded soft clay on the column.

In Figure 4, it is predicted immediately after the column installation a minor decrease of soft clay Young modulus. However, this fact might be counterbalanced since the radial drainage will occur during the consolidation of soft clay for a period of eleven months.

The second phase corresponds to the end of radial consolidation in soft clay that was estimated roughly of eleven (11) months. Therefore excess pore pressures generated in the soft clay, especially at column vicinity, are dissipated by radial drainage towards the column. Figure 5 shows the degree of consolidation of soft clay as a function of horizontal distance.

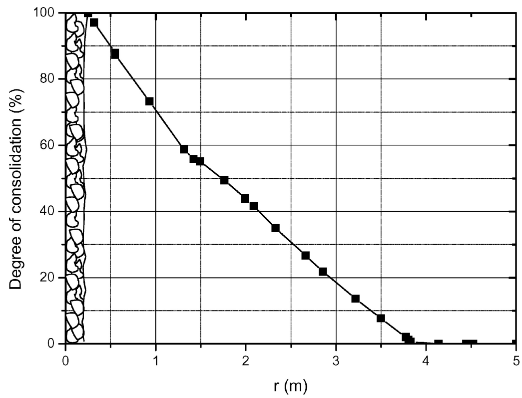

Figure 5. Degree of consolidation at mid-thickness of soft clay, after consolidation.

The corresponding stress distribution in terms of normalized ratios, with respect to initial values, is presented in Figure 6.

The vertical effective stress is slightly modified after the consolidation of soft clay. But the significant increase of horizontal effective stress is quasi-identical to that of effective mean stress.

By using the hardening soil model the expected increase of secant Young modulus in soft clay is determined (Figure 7). Such a stiffness improvement is due to the increase of effective horizontal stress. From which it is estimated the soft clay improvement stops at 2 m distance from the columns axis. The mean value of stiffness modulus increase is of about 40% which is not negligible.

5 CONCLUSIONS AND PERSPECTIVES

In this study the aim was to predict the improvement of soft clay Young modulus resulting from stone column

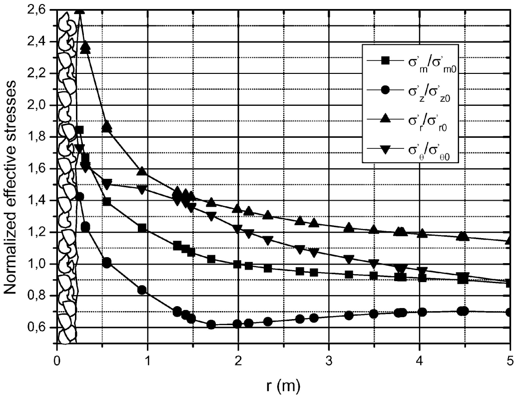

Figure 6. Normalized effective stresses distribution mid-thickness of soft clay, after consolidation.

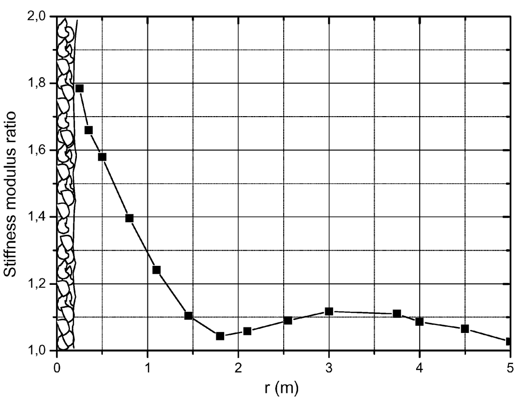

Figure 7. Stiffness modulus ratios at mid-thickness of soft clay, after consolidation.

installation. For this purpose, a numerical simulation was performed using the finite element code Plaxis 8.1. This procedure involves the use of a hardening soil model which takes into account the stiffness-stress dependency for soft clay. The calibration of the constitutive model parameters is done by a simulation of laboratory tests and the comparison between experimental results and predicted ones.

Then, the increase of stiffness is evaluated at the middle of soft clay layer after the consolidation generated by the column installation.

The numerical implementation of hardening soil model, showed up the significant influence of column installation on the increase of soil stiffness after the period of consolidation. The predicted increase of soft clay Young modulus is in average of about 40% the initial value. This improvement occurs in distance equals three times the column radius.

The advantage in determining the influence zone radius is to optimise the spacing between columns along which the improvement of stiffness modulus is completely effective. The regardless of this improvement may also induce the current design methods to overestimate the required quantities of incorporated column material.

The consolidation period preceding the loading has an important role on this improvement and it should be considered for settlement prediction.

This contribution only focused on the effect of column installation and consolidation preceding the loading of the reinforced soil. The influence of final loading on the behavior of reinforced soil shall be investigated in a further work.

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