Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0170

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Effect of stone columns encasement on consolidation of soft soil

Effet de l'enrobage de colonnes ballastées sur la consolidation d'un sol meuble

B. Pulko
UL, Faculty of Civil an Geodetic Engineering, Ljubljana, Slovenia

J. Logar
UL, Faculty of Civil an Geodetic Engineering, Ljubljana, Slovenia

ABSTRACT: The aim of this paper is to present the basics and to demonstrate the ability of the recently developed method (Pulko and Logar, 2017b) for the consolidation analysis of soft ground improved by geosynthetic-encased stone columns (GESCs). The method, developed in the framework of Biots's consolidation theory, is based on the unit cell concept and takes into account poroelastic cylinder of soil and GESC and provides fully coupled solution of equilibrium and diffusion equations. The calculation of settlements, excess pore pressure, stresses and encasement forces in time domain is based on the numerical inverse of analytical expressions obtained in Laplace domain. The advantage of the proposed method is that it enables consideration of time dependent loading, takes into account subsequent transfer of stresses from the soil to the column and provides settlement rate prediction. The results of parametric study on a number of governing factors, such as area replacement ratio and encasement stiffness, show significant impact on the transient stress states and on the rate of settlements. It is also shown that additional confinement provided by the geosynthetic encasement can substantially speed up the consolidation process as compared to widely used Barron's solution (1948).

RÉSUMÉ: L'objectif de cet article est de présenter les bases et de démontrer l'aptitude de la méthode récemment développée (Pulko et Logar, 2017b) pour l'analyse de la consolidation du sol meuble, améliorée par des colonnes ballastées recouvertes de géosynthétique (GESC). La méthode, développée dans le cadre de la théorie de consolidation de Biots, est basée sur le concept de cellule unitaire et prend en compte le cylindre poroélastique du sol, des GESC et fournit une solution entièrement couplée d'équations d'équilibre et de diffusion. Le calcul des tassements, de l'excès de pression dans les pores, des contraintes et des forces d'enrobages dans le domaine temporel est basé sur l'inverse numérique des expressions analytiques obtenues dans le domaine de Laplace. L'avantage de la méthode est qu'elle permet de prendre en compte la charge en fonction du temps, prend en compte le transfert ultérieur des contraintes du sol à la colonne et fournit une prédiction du taux de règlement. Les résultats d'une étude paramétrique sur un certain nombre de facteurs déterminants, tels que le taux de remplacement de la surface et la rigidité de l'enveloppe, montrent un impact significatif sur les états de contraintes transitoires et sur le taux de tassement. Il est également démontré qu'un confinement supplémentaire fourni par l'enveloppe géosynthétique peut considérablement accélérer le processus de consolidation par rapport à la solution largement utilisée de Barron (1948).

Keywords: Encased Stone Columns; Ground improvement; Consolidation; Elastoplasticity; Poroelasticity

1 INTRODUCTION

The stone columns (SC) are frequently used to improve the bearing capacity and reduce the settlement of soft ground under various loads. The beneficial effect of stone column installation results in increased stiffness and strength, reduced settlements, increased rate of settlements and reduction of liquefaction potential. These improvements can be significantly enhanced by encapsulation of the stone columns into geosynthetic sleeve to form what is called geosynthetic encased stone columns (GESC).

Most of the analytical methods for settlement prediction of foundations resting on a large number of end-bearing ordinary stone columns (OSC) or GESC are based on the unit cell concept, adopting drained conditions and either elastic or elasto-plastic approach (Balaam and Booker, 1985; Priebe, 1995; Pulko and Majes, 2006; Castro and Sagaseta, 2009; Raithel and Kempfert, 2000; Pulko et. al., 2011). It should be noted that most of methods focus on the settlement reduction and not on consolidation of the stabilized soil. However, the stone columns also act as effective vertical drains and can dissipate the excess pore pressures and therefore significantly increase the rate of consolidation.

Most often the consolidation process is analysed independently using well-known solution for vertical drains (Barron, 1948) which does not take into account the redistribution of soil and SC stresses during ongoing consolidation. For GESC this shortcoming was first overcome by closed-form analytical elastic solution by elasto-plastic Castro and Sagaseta (2011, 2013) where undrained loading is followed by a consolidation process based on Barron's solution (Barron, 1948).

Recently, a fully coupled semi-analytical solution of equilibrium and diffusion equations was developed for OSC and GESC (Pulko and Logar, 2017a, 2017b), where the poroelastic solution for thick-walled cylinder (Jourine et al. 2004), developed within the framework of Biots's consolidation theory (Biot, 1941) has been coupled with permeable elasto-plastic stone column to obtain analytical expressions for displacements, stresses and excess pore pressures in the Laplace domain. The method is also capable to take into account time dependent loading. The aim of this paper is to present the basics and to demonstrate the ability of this recently developed method (Pulko and Logar, 2017b) for the analysis of GESC and to show how some governing factors affect settlements and consolidation process.

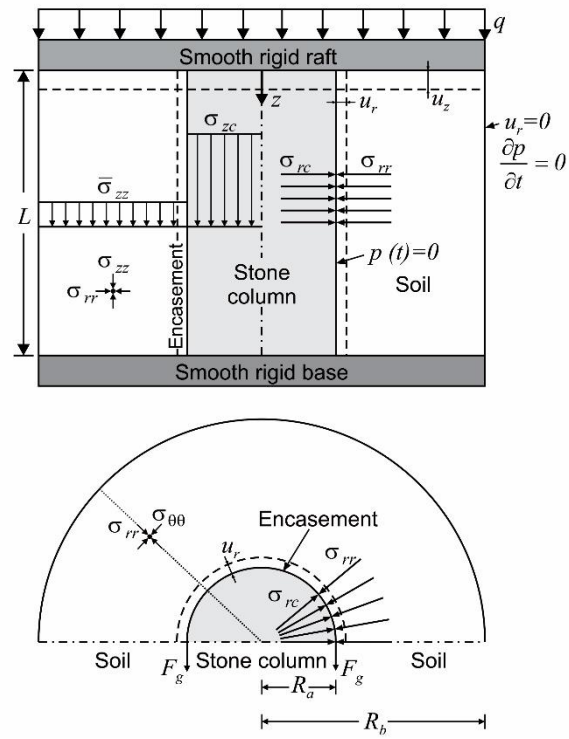

Figure 1. Unit-cell axisymmetric representation of stone column and surrounding soil

2 METHOD DESCRIPTION

The details of the method are given in the paper of Pulko and Logar (2017b) and therefore, only the basics are given herein. The unit cell concept was adopted for the analysis, consisting of a saturated thick-walled poroelastic cylinder, permeable non-associative elasto-plastic stone column

(Mohr – Coulomb) and tensile resistant encasement (e.g. geosynthetic) as shown in Figure 1. The cylindrical coordinates (r, θ, z), compression negative notation for stresses and strains and positive notation for excess pore pressures were adopted.

The solution for poroelastic thick-walled cylinder (Jourine et al., 2004) gives analytical expressions for stresses, strains and excess pore pressures and displacements in the Laplace domain in terms of material constants (Jourine et al., 2004) and modified Bessel functions. Analytical expressions include four coefficients and vertical strain $\widetilde{\varepsilon_{zz}}$, that must be determined based on equilibrium and compatibility conditions of the unit cell depending on either elastic or plastic column behaviour and time dependent load. The elastic and plastic time domain solutions require numerical inversion of the Laplace transform, with the final elastoplastic solution for stresses, strains, excess pore pressures, displacements and encasement forces for the preselected depth z and time t obtained as linear combination of elastic and plastic solutions (Pulko and Logar, 2017a, 2017b). It should be noted that the final settlements according to this method match the results of drained solution presented by Pulko et al. (2011) and Castro and Sagaseta (2013).

3 METHOD EVALUATION

To demonstrate the ability of the developed method, results are presented and compared to the axisymmetric finite element (FE) analysis using Plaxis 2D (Brinkgreve et al., 2016). The unit cell consists of 10 m long stone column with a radius of 0.4 m. Numerical model was set up with restricted horizontal displacements at the surface and at the base of the unit cell in order to simulate perfectly rough conditions. The replacement ratio $N = R_b/R_a = 3$ was initially taken into account while varying encasement stiffness in the range of $J_g = 0 - 4$ MN/m.

The material data for the soil and stone column material are given in Table 1. Due to the poroelastic approach, in addition to the standard material data, the undrained Poisson's ratio υ_u and Skempton's parameter B (Skempton, 1954) had to be specified for the soil.

Table 1. Material properties

Material property	Soil	SC
Unit weight, γ [kN/m^3]	20.0	20.0
Young's modulus, E [MPa]	1.0	40.0
Poisson's ratio, υ / υ_u	0.3/0.495	0.3 / -
Skempton's parameter, B	0.9783	-
Hydraulic conductivity, k [m/s]	10^{-9}	1.0
Friction angle [°]	-	40.0
Dilatancy angle [°]	-	10.0

The water table was set at the surface where instantaneous vertical load -100 kPa is applied upon stiff plate. Initial lateral stresses were generated by taking into account the coefficient of lateral earth pressure $K_{ini} = 0.6$.

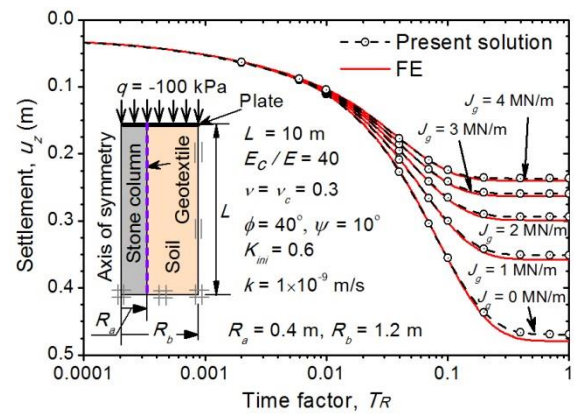

Figure 2. Settlements versus time factor for encasement stiffnesses $J_g = 0 - 4$ MN/m

Figure 2 shows settlements as calculated with the developed method and FE analyses versus time factor $T_R = C_r\, t/(2R_b)^2$ defined in terms of the radial coefficient of consolidation C_R:

$$C_R = \frac{k\, E_{oed}}{\gamma_w} = 1.346 \times 10^{-7}\ \text{m}^2/\text{s} \qquad (1)$$

The effect on settlement reduction as the encasement stiffness increases is very pronounced, as shown in Figure 2.

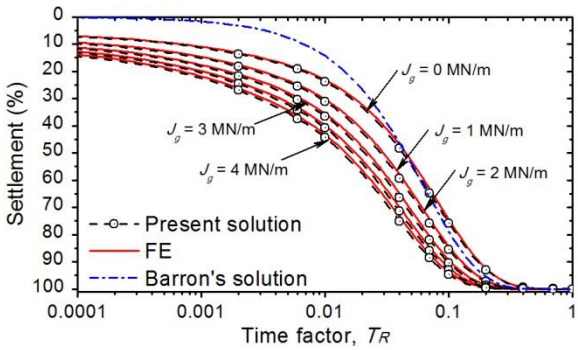

Figure 3. Rate of settlements for encasement stiffnesses $J_g = 0 - 4$ MN/m

Figure 3 shows the normalized values of settlements versus time factor. Both methods agree well, showing high impact of the encasement stiffness on consolidation process. The Barron's solution is also shown for the sake of comparison and exhibits much slower consolidation.

At the time of loading, some immediate settlement occurs simultaneously with excess pore water pressures increase. At this point the soil is in the undrained state, behaves very stiffly and thus takes most of the imposed load. As the consolidation starts, the soil stiffness decreases with ongoing settling. Due to the soil-column stiffness difference significant stress transfer from the soil to the column occurs and continues throughout the consolidation as long as the (encased) SC is able to take the load. The stiffer the encasement, the higher is the ability of the SC to take the load and thus, the higher is the reduction of imposed total stresses in the soil, which also means simultaneous reduction in the excess pore pressures.

Contrary to the proposed method, the Barron's solution for radial consolidation assumes constant total stresses throughout the consolidation and cannot satisfactorily describe the consolidation of GECS improved ground.

4 PARAMETRIC STUDY

Parametric study was performed with the above described numerical model and with encasement stiffness equal to $J_g = 2$ MN/m to study the influence of several model parameters on the settlement and consolidation behaviour of GESC improved ground.

4.1 The impact of SC shear strength

In order to study the influence of SC shear strength on settlement and consolidation behaviour the shear angles of the SC material of 30°, 40° and 50° were adopted.

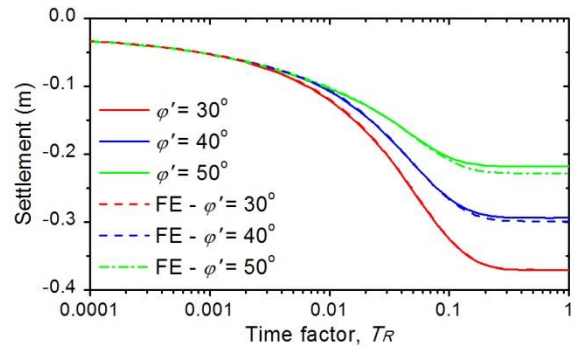

Figure 4. Settlements versus time factor for $\varphi' = 30° - 50°$

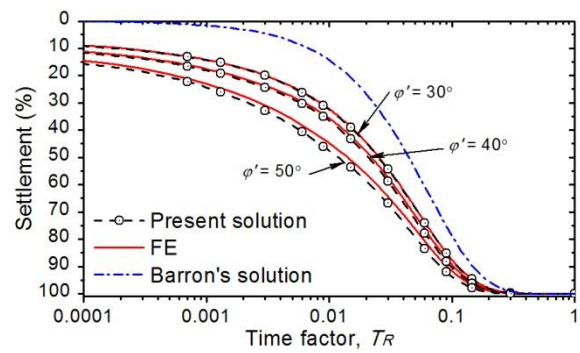

Figure 5. Rate of settlements for $\varphi' = 30° - 50°$

The SC shear strength has significant impact on settlement reduction and on consolidation process of the improved ground (Figures 4 and 5). As the shear angle of SC increases the final set-

tlement decreases with an increased consolidation speed, where final consolidation time is hardly affected.

4.2 The impact of stiffness ratio

Contrary to the SC shear strength, the stiffness ratio between the SC and soil E_c/E_s has hardly any effect on the consolidation rate as shown in Figure 7. While the higher stiffness ratio E_c/E_s leads to settlement reduction (Figure 6), there is negligible effect on the consolidation process.

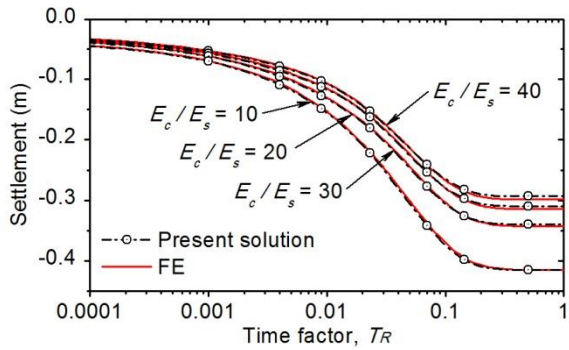

Figure 6. Settlements versus time factor for $E_c/E_s = 10 - 40$ *(*$J_g = 2$ *MN/m)*

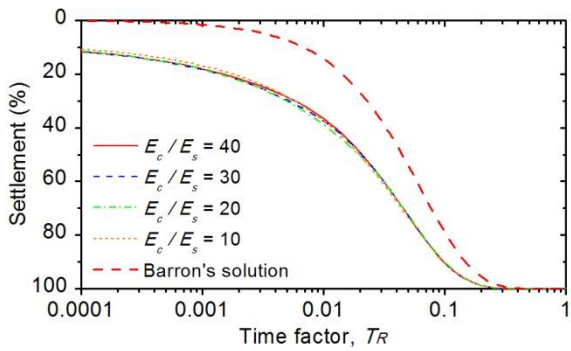

Figure 7. Rate of settlements for $E_c/E_s = 10 - 40$ *(*$J_g = 2$ *MN/m)*

4.3 The influence of initial stress state

The initial lateral stresses on the soil-column interface depend on the installation technique and can be taken into account through the lateral earth coefficient K_{ini}. While the value of K_{ini} plays an important role in settlement reduction for OSC, its impact with the use of encasement is less pronounced (Figure 8) and almost negligible when it comes to the time rate of settlements (Figure 9).

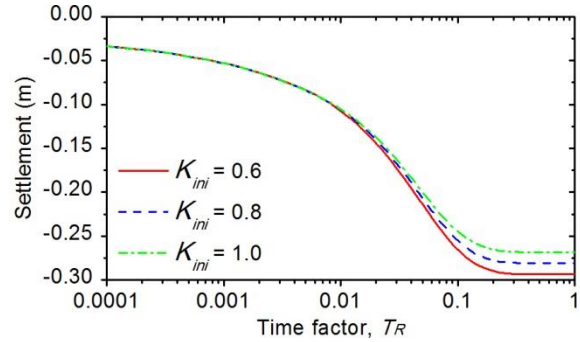

Figure 8. Settlements versus time factor for $K_{ini} = 0.6 - 1.0$ *(*$J_g = 2$ *MN/m)*

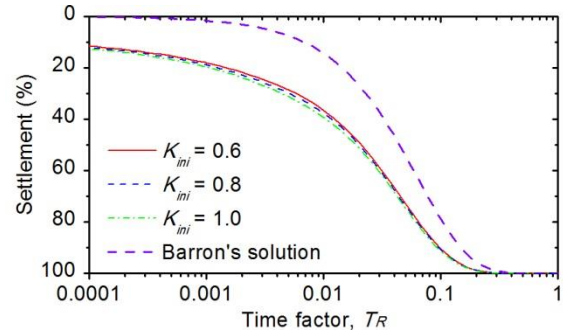

Figure 9. Rate of settlements versus time factor for $K_{ini} = 0.6 - 1.0$ *(*$J_g = 2$ *MN/m)*

4.4 The influence of dilation angle

The dilation angle ψ of the SC material plays an important role in settlement reduction. Once the ratio between vertical and radial stresses in the SC reaches the failure state, plastic straining occurs. If the column material is dense enough, it will exhibit dilation and will therefore have a positive impact on settlement reduction. This can be clearly observed in Figure 10, where settlements are depicted versus time factor. However, the influence on the time rate of settlement process is rather small (Figure 11). Note also,

that Barron's solution, like in other comparisons, predicts a much slower settling.

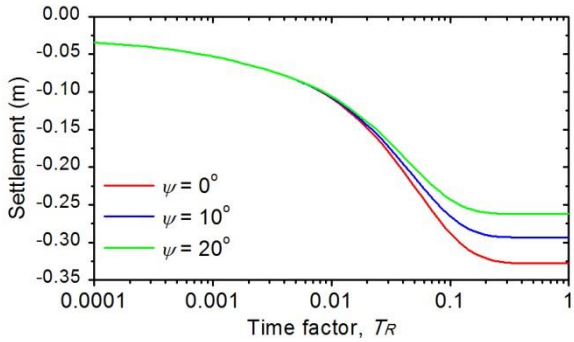

Figure 10. Settlements versus time factor for $\psi = 0° - 20°$

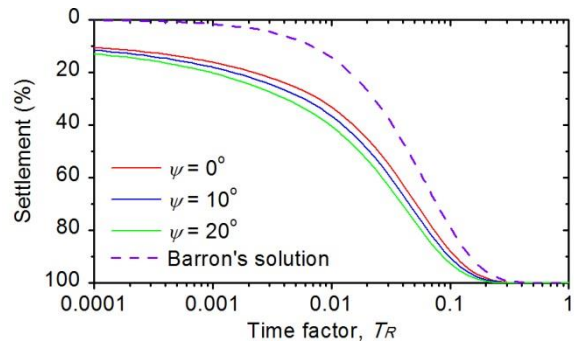

Figure 11. Rate of settlements versus time factor for $\psi = 0° - 20°$ ($J_g = 2$ MN/m)

4.5 The influence of replacement ratio and encasement stiffness

The replacement ratio $N = R_b/R_a$ has the most significant impact on the consolidation process and settlement reduction of the OSC or GESC improved ground. The impact on settlements is usually expressed as a settlement reduction ratio β, defined as a ratio between the final settlements of improved and non-improved ground. The drained solution presented by Pulko et al. (2011) has proved that under certain load, and by taking into account the initial stresses (K_{ini}), the final settlement reduction factor β is essentially a function of the replacement ratio N, the stiffness ratio E_c/E_s, the SC shear angle φ', the SC dilation angle and non-dimensional encasement stiffness T, which is defined as:

$$T = \frac{J_g}{E_s R_a} \tag{2}$$

The drained Poisson's ratios of the soil and SC material have proved to have insignificant impact on the results, as long as they are within the range of realistic values.

In order to investigate, whether the time rate of settlements can also be evaluated in a dimensionless form of replacement ratio N and encasement stiffness T, additional analyses were performed. It turned out that, for the adopted replacement ratio N, load stiffness ratio E_c/E_s, given set of soil (γ, ν, ν_{ur}, B) and SC material parameters ($\gamma, \nu, \varphi', \psi$), and adopted value of K_{ini}, it is possible to express the settlement reduction factor β as a function of the non-dimensional encasement stiffness T and time factor of radial consolidation T_R. The results for the adopted set of material parameters (Table 1) in terms of settlement reduction factor β versus time factor T_R for values of replacement ratios N = 2 to 5 are shown in Figures 12 to 15.

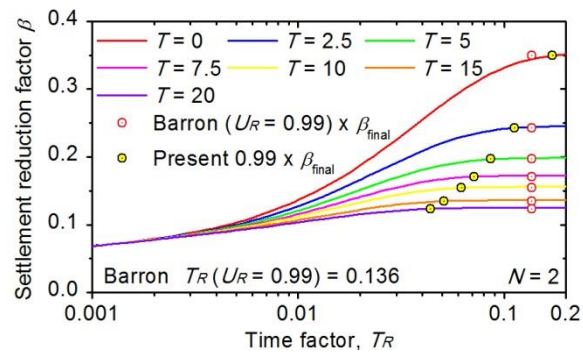

Figure 12. Results for N = 2

The positive impact of the replacement ratio N and non-dimensional encasement stiffness T on the settlement reduction is expected. However, the effect on the consolidation is more interesting. As the non-dimensional encasement stiffness increases the consolidation time decreases.

The yellow circles shown in Figures 12 to 15 indicate 99 % of the final settlement reduction factor β and mark the corresponding time factor T_R according to the method of Pulko and Logar (2017b). For comparison, the values (red dots) according to Barron's solution for the achieved 99 % degree of consolidation applied onto the same final settlements are also depicted.

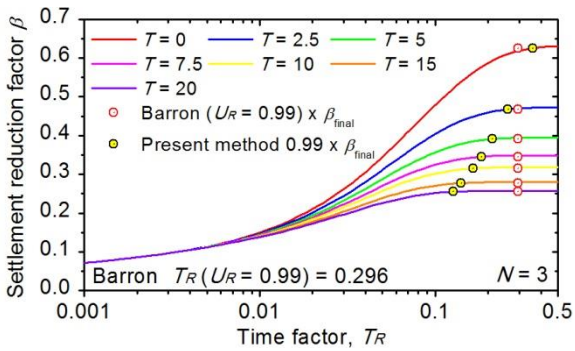

Figure 13. Results for N = 3

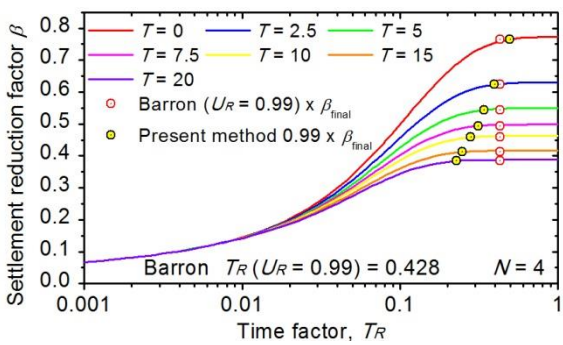

Figure 14. Results for N = 4

We can see that OSC initially accelerate consolidation (Figure 3) due to the initial stress transfer, but the process slows down towards the end of consolidation and predicts slightly longer consolidation times as compared to Barron's solution. As the encasement stiffness T increases, not only it enables more stress to be taken by the GESC, but also accelerates the consolidation process and reduces the consolidation time. This is especially prominent for the tightly spaced columns, where consolidation proceeds much faster as compared to Barron's solution, which is not able to take stress concentration in the GESC into account.

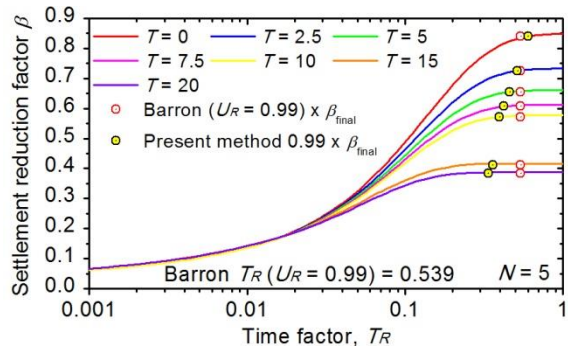

Figure 15. Results for N = 5

Figure 16 shows the ratio of time needed to achieve 99 % degree of consolidation according to the proposed analytical solution and Barron's solution for different replacement ratios and non-dimensional encasement stiffnesses. As the ratio N decreases and non-dimensional encasement stiffness T increases the consolidation time shortens to a considerable extent when compared to Barron's solution.

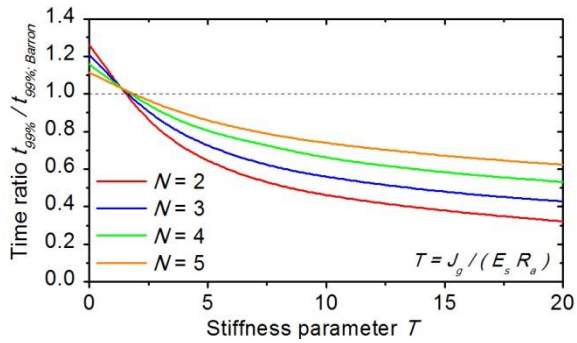

Figure 16. The effect of replacement ratio and encasement stiffness on the consolidation time

5 CONCLUSIONS

A recently developed fully coupled elastoplastic solution for the response of an elastoplastic encased stone column and poroelastic soil (Pulko

and Logar, 2017b) is briefly presented through examples/parametric study. Based on the presented results the following conclusions can be drawn:

- The presented solution is capable of taking into account instantaneous or time dependent increasing load and of predicting settlements and transient distributions of excess pore pressures, stresses and deformations. Other factors usually associated with stone columns, such as stress concentration factor (SCF) and settlement reduction factor β can be calculated accordingly at any selected time.
- It has been demonstrated that the proposed method is capable of giving results in very good agreement with elasto-plastic FE analyses throughout the consolidation process.
- The final settlements according to the proposed method match the results of drained solution presented by Pulko et al. (2011) and Castro and Sagaseta (2013).
- Besides the replacement ratio, the encasement stiffness plays a key role in reducing settlements and consolidation time.
- The design of GECS which is based on the separate calculation of final settlements and then combined with Barron's solution for radial consolidation generally overestimates the final consolidation time. This is not necessarily bad, as the predicted time is usually on the safe side, but by using more advanced methods, more reliable prediction of consolidation can be achieved.

6 REFERENCES

Balaam, N.P., Booker, J.R., 1985. Effect of stone column yield on settlement of rigid foundations in stabilized clay. Int. J. Numer. Anal. Methods Geomech. 9, 331-351.

Barron, R.A., 1948. Consolidation of fine-grained soils by drain wells. Trans. Am. Soc. Civ. Eng. 113, 718-742.

Biot, M.A., 1941. General theory of three-dimensional consolidation. J. Appl. Phys. 12, 155-164.

Brinkgreve, R.B.J., Kumarswamy, S., Swolfs, W.M., 2016. Plaxis 2D 2016. Plaxis bv, Netherlands.

Castro, J., Sagaseta, C., 2011. Deformation and consolidation around encased stone columns. Geotext. Geomembr. 29, 268-276.

Castro, J., Sagaseta, C., 2013. Influence of elastic strains during plastic deformation of encased stone columns. Geotext. Geomembr. 37, 45-53.

Jourine, S., Valkó, P.P., Kronenberg, A.K., 2004. Modelling poroelastic hollow cylinder experiments with realistic boundary conditions. Int. J. Numer. Anal. Methods Geomech. 28, 1189-1205.

Priebe, H.J., 1995. The design of vibro replacement. Ground Eng. 28, 31-37.

Pulko, B., Majes, B., 2006. Analytical method for the analysis of stone-columns according to the Rowe dilatancy theory. Acta Geotech. Slov. 2006, 38-45.

Pulko, B., Majes, B., Logar, J., 2011. Geosynthetic-encased stone columns: analytical calculation model. Geotext. Geomembr. 29, 29-39.

Pulko, B., Logar, J. (2017a). Fully coupled solution for the consolidation of poroelastic soil around elastoplastic stone column. Acta Geotech. 12(4), 869-882.

Pulko, B., Logar, J. (2017b). Fully coupled solution for the consolidation of poroelastic soil around geosynthetic encased stone columns. Geotext. Geomembr. 45(6), 616-626.

Raithel, M., Kempfert, H.G., 2000. Calculation models for dam foundation with geotextile coated sand columns. In: Proc. of Int. Conf. on Geotech. and Geol. Eng., GeoEng 2000. CRC Press, Melbourne, Australia, pp. 347-352.

Skempton, A.W., 1954. The pore-pressure coefficients A and B. Géotechnique 4, 143-147.