

# Consolidation analysis around cavity expansion in presence of vertical drains

Zeineb Ben Salem<sup>1\*</sup>, Marwa Ben Khalifa<sup>2</sup>, Wissem Frikha<sup>3</sup>

<sup>1</sup>Univ.de Carthage, Institut Supérieur des Technologies de l'Environnement de l'Urbanisme et de Bâtiment, 2 Rue de l'Artisanat Charguia 2 - 2035 Tunis, Tunisia

<sup>2</sup>Univ. de Tunis El Manar, Ecole Nationale d'Ingénieurs de Tunis, LR14ES03-Ingénierie Géo-technique, BP 37 Le Belvédère, 1002 Tunis, Tunisia

<sup>3</sup>Univ. de Tunis El Manar, Ecole Nationale d'Ingénieurs de Tunis, LR14ES03-Ingénierie Géotechnique, BP 37 Le Belvédère, 1002 Tunis, Tunisia,

Setec International 42-52 Quai de la Rapée Central Seine Building 75583 Paris Cedex 12. France

**Abstract.** As a ground improvement technique, the new method composed by a cylindrical cavity expansion (CCE) combined with vertical drains (VD) greatly accelerates the consolidation of soft soil. In fact, the cylindrical cavity applies a radial displacement in the soil. Excess pore pressures will be consequently generated and the consolidation process will occur at the vicinity of the cavity wall. The dissipation of excess pore pressures can be enhanced in presence of VD installed at a radial distance  $r_d$  from the center of the cylindrical cavity. Because of CCE installations in soft soil, surrounding soil properties are altered in such a manner that horizontal permeability of the soil in the smear zone reduces. The purpose of the present paper is to investigate the subsequent consolidation around CCE using the Finite Difference Method (FDM) by taking into account the CCE installation disturbance. Parametric analysis aimed to investigate the effect of the extent of the disturbed zone, the soil permeability reduction in the smear zone on the rate of consolidation around CCE.

## 1 Introduction

Construction on soft soils raises serious geotechnical problems, one of which is a consolidation settlement that lasts for a long time due to their low shear strength, highly compressibility and their low permeability.

Several ground improvement techniques have been developed to accelerate soft soils consolidation process. These techniques mainly include stone columns, preloading method with vertical drains VD, vacuum preloading, etc. [1, 2, 3].

The technique of combining two ground improvement methods has been successfully used worldwide by geotechnical practitioners such as the combined Dry jets mixing technique with VD stone columns technique encased with geosynthetics [4, 5].

---

\* Corresponding author: [zeineb.bensalem@gmail.com](mailto:zeineb.bensalem@gmail.com)

The present paper aims to investigate the acceleration of consolidation of soft soil through a new method composed by a cylindrical cavity expansion (CCE) combined with vertical drains (VD) [6, 7].

As a response of cavity displacement, excess pore pressures are generated in the soil and the consolidation process will occur at the vicinity of the cavity wall. The dissipation of excess pore pressures will be enhanced in presence of VD. Because of CCE installation in soft soil, surrounding soil properties is altered in such a manner that horizontal permeability of the soil in the smear zone reduces. In this paper, the subsequent consolidation around CCE using the Finite Difference Method (FDM) is analysed by taking into account the CCE installation disturbance. Parametric analysis is undertaken to investigate the effect of the extent of the disturbed zone and the soil permeability reduction in the smear zone on the rate of consolidation around CCE.

## 2 Cylindrical cavity expansion around vertical drains

In this paper, the new consolidation technique consists of combining cylindrical cavity expansion with vertical drains (VD) [6, 7]. Cylindrical cavity is composed of a radial expansible and impervious material and installed in a predrilled borehole surrounded by VD in a triangular grid pattern at radial distance  $r_d$  as presented in Fig 1 and 2.

The cylindrical cavity is subjected to an internal pressure  $\sigma_0$ . As a response to the internal pressure, an excess of pore water pressure is generated within the soil in the plastic zone of radius  $R_p$ . The acceleration of the dissipation of excess pore pressures with the presence of VD increase the rate of radial consolidation in soil. In fact, VD reduces the drainage path by providing radial drainage controlled by their dimension and their discharge capacity.

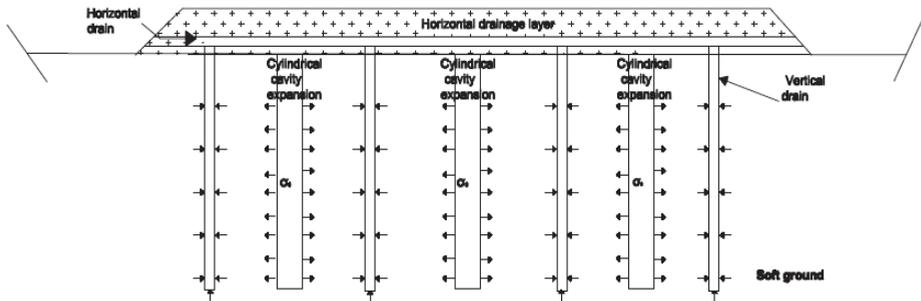


Fig.1. Cross section of the consolidation method

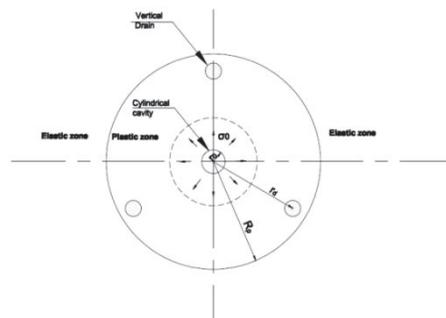


Fig. 2. CCE in presence of VD

### 3 Installation disturbance around CCE

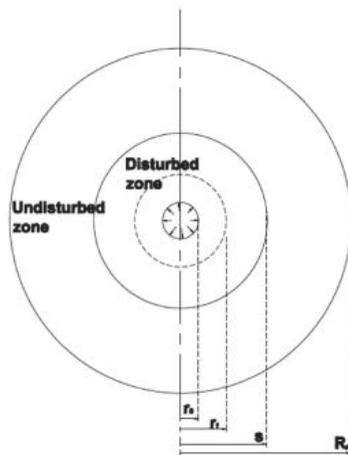
Because of CCE installation in soft soil, surrounding soil properties are altered in such a manner that horizontal permeability of the soil at the vicinity of the cylindrical cavity in the smear zone reduces. [8]. The smear zone around the cylindrical cavity is defined by the radius  $s$  as shown in Figure 3. The variation of horizontal permeability  $k(r)$  with radial distance  $r$  counted from the center of the cylindrical cavity ranges from  $k_s$  to  $k_i$  ( $k_s < k_i$ ). The value of  $k_i$  is the initial horizontal permeability in the soil and,  $k_s$  is the minimum value of horizontal permeability (Figure 3).

Several researches have been conducted to characterize the extent of the smear zone and the reduction of horizontal permeability within this zone using the cylindrical cavity expansion theory. Different variation patterns of horizontal permeability within the smear zone can be considered: reduced constant permeability, linear and parabolic variation of permeability [8, 9, 10].

Around a cylindrical cavity, the horizontal permeability of soil  $k(r)$  in the disturbed zone is assumed to have a linear variation in the present study:

$$k(r) = \frac{k_i - k_s}{s - r_f} (r - r_f) + k_s \quad (1)$$

Where  $r_f$  is the final radius of the cylindrical cavity after expansion.



**Fig.3.**The smear zone around cylindrical cavity expansion

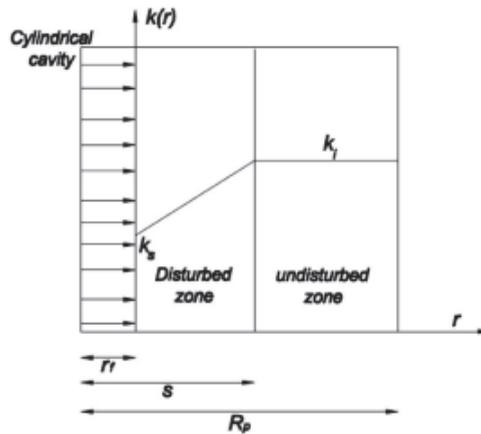


Fig.4. Variation of horizontal soil permeability around cavity expansion.

### 4 Consolidation around CCE

Under undrained condition and based on the Tresca yield criterion, the generated excess pore pressures  $\Delta u$ , at radial distance  $r$  from the center of cavity expansion is given by the expression:

$$\Delta u = 2C_u \ln \frac{R_p}{r} \tag{1}$$

where  $C_u$  is the undrained cohesion and  $R_p$  is the elastic plastic boundary given by:

$$R_p^2 = \frac{1}{r_0^2} \cdot \frac{G}{C_u} \cdot \frac{\Delta v}{\Delta v_0} \tag{2}$$

$\Delta v/v_0$  and  $G$  denote, respectively, the expand cavity volume and the shear modulus of soil. By considering  $\Delta U = \Delta u / \Delta u_{max}$ ,  $R = r/r_f$ ,  $T = C_h t / r_f^2$  and  $K(R) = k(r)/k_i$ , the governing equation for the subsequent radial consolidation by taking account of the variation of horizontal permeability  $k(r)$  is written as:

$$\frac{\partial \Delta U}{\partial T} = K(R) \left( \frac{\partial^2 \Delta U}{\partial R^2} + \frac{1}{R} \frac{\partial \Delta U}{\partial R} \right) + \frac{\partial [K(R)]}{\partial R} \frac{\partial \Delta U}{\partial R} \tag{3}$$

Where  $\Delta u_{max}$  is excess pore pressures at the border of the cavity after expansion, i.e., for  $[R=1]$  ( $r = r_f$ , i.e final radius of CCE) at  $[T=0]$ , ( $t=0$ ) (initial condition),  $C_h$  = radial consolidation coefficient of the soil.

At the border of the cavity expansion ( $r=r_f$ ), the rate of variation of  $\Delta u$  due to symmetry is equal to zero.

The calculation process of the governing equation of the dissipation of excess pore pressure around CCE (Eqs. (3)) is detailed in Figure 5. The governing equation was solved with a FDM using MATLAB software. The following analyses were made with an initial radius  $r_0 = 0.2m$ ,  $G/ C_u = 20$  and a volume variation  $\Delta v/v_0 = 2$ .

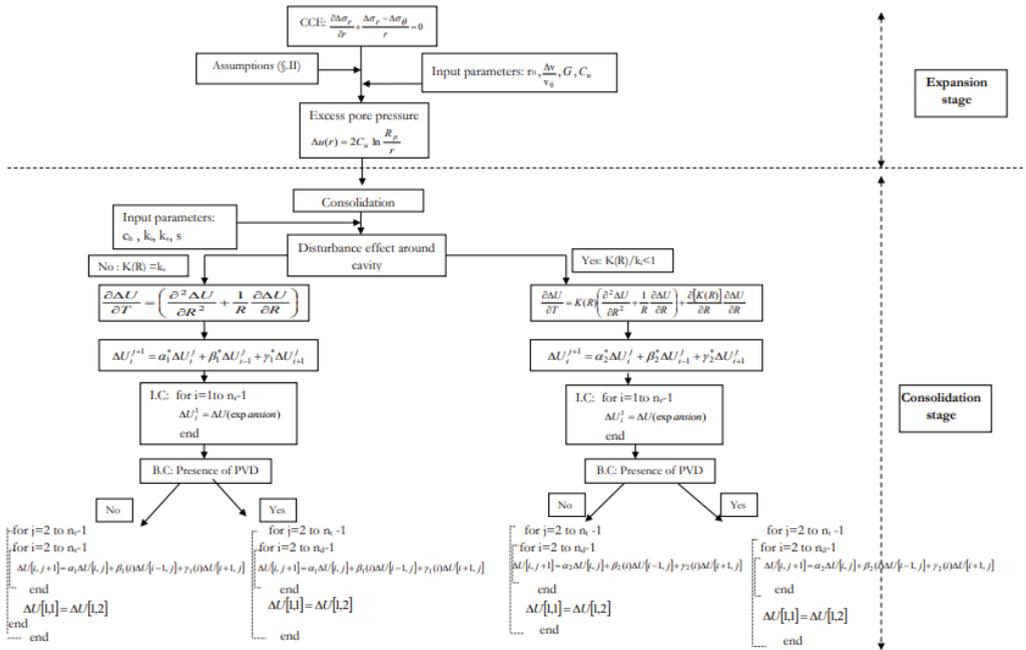
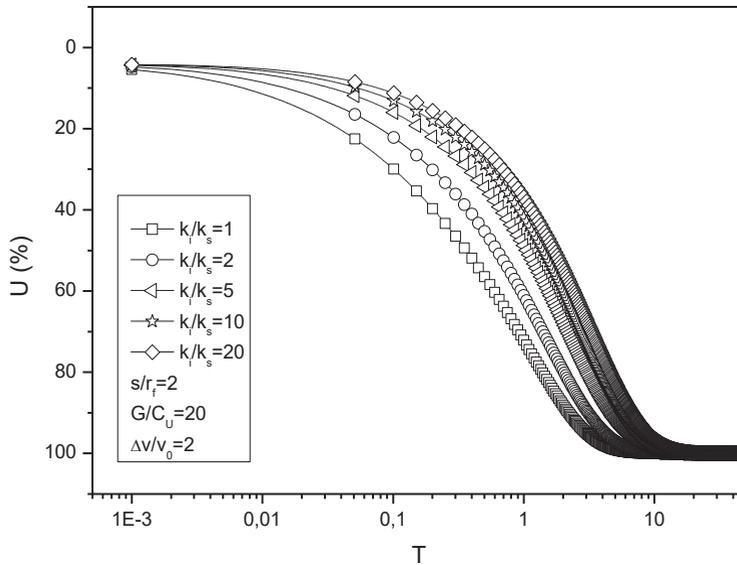


Fig.5. Calculation process [6]

### 5 Effect of the soil permeability reduction in the smear zone on the consolidation around CCE

For a given ratio  $s/r_f=2$ , the influence of soil permeability reduction  $k_i/k_s$  in the smear zone on the degree of consolidation  $U$  (%) with time factor  $T$  calculated at the cavity wall is analysed as shown in Figure 6. The range of the permeability ratio  $k_i/k_s$  of 1 to 20 was analyzed.

In the case where  $k_i/k_s = 1$ , i.e., (without variation of soil permeability), total dissipation occurs at  $T= 19$ . On the other hand, considering the reduced permeability in the disturbed zone  $k_i / k_s > 1$ , total dissipation of excess pore water pressure occurs at time factor  $T$  always greater than 19 ( $T > 19$ ). It can be seen that, the required time of total dissipation increases as horizontal permeability in the disturbed zone  $k_s$  decreases. When  $k_i/k_s = 2$  and 5, total dissipation occurs at  $T=26$  and  $T= 36$ , respectively. Whereas, when  $k_i/k_s$  is greater than 5 ( $k_i/k_s=10$  and 20), the end of consolidation is reached for final consolidation time factor  $T$  of around 40. It, can be seen that the ratio  $k_i/k_s$  has no significant effect on the variation of the degree of consolidation  $U$  (%) beyond  $k_i/k_s = 5$ .



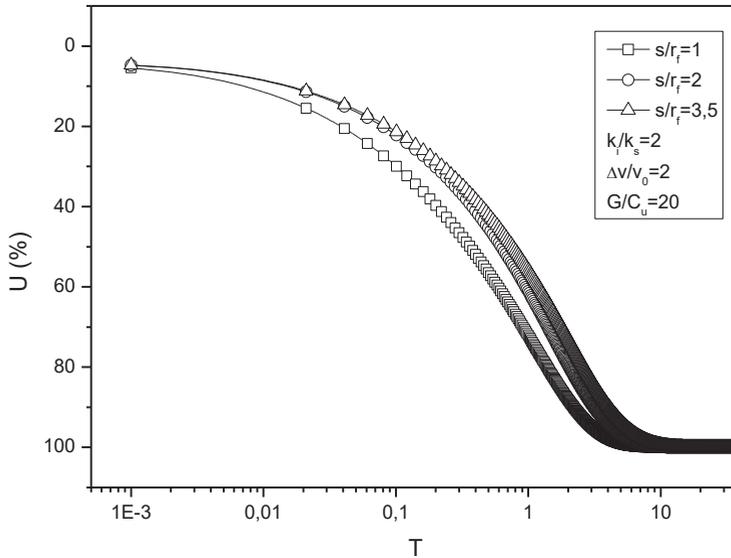
**Fig.6.** Effect of  $k_i/k_s$  on the variation of the degree of consolidation  $U$  (%) at the cavity wall

## 6 Effect of the extent of the smear zone on the consolidation around CCE

For a given permeability ratio  $k_i/k_s = 2$ , Figure 7 shows the effect of the extent of the smear zone  $s/r_f$  on the variation of the degree of consolidation  $U$  (%) with time factor  $T$ . As shown in Figure 4,  $s/r_f$  varies from 1 (without considering the disturbed zone) to  $R_p/r_f$  (the plastic zone  $R_p$  generated after CCE is entirely disturbed).

Referring to the Eq. (2),  $R_p/r_f$  is then equal to 3.65. Consequently, the range of the ratio  $s/r_f$  is of 1 to 3.5.

As presented in Figure 7, for the case where  $s/r_f = 1$  (without considering the disturbed zone) the total dissipation of excess pore water pressure occurs at a time factor  $T = 19$ . On the other hand, with the presence of the disturbed zone  $s/r_f > 1$  ( $s/r_f = 2$  and 3.5) the end of consolidation occurs at  $T = 26$  and 35, respectively. The presence of the disturbed zone reduces the pore water pressure dissipation around CCE.



**Fig.7.** Effect of  $s/r_f$  on the variation of the degree of consolidation  $U$  (%) at the cavity wall

## 7 Conclusion

In this paper, the subsequent consolidation around cavity expansion in presence of vertical drains was investigated. The governing equation for the dissipation of excess pore pressure induced by cavity expansion, has been solved with a Finite Difference Method (FDM) using MATLAB software. By considering installation effect of cavity expansion, slower rate of dissipation is observed with larger smear zone and reduced horizontal permeability within this zone. This effect reduces the time required for full dissipation ( $U=100\%$ ) by 50%.

## Reference

1. B. Indraratna, C. Rujikiatkamjorn, A.S. Balasubramaniam, and G. McIntosh, G. “Soft ground improvement via vertical drains and vacuum assisted preloading.” *Geotex. and Geom., Els. Ltd*, 30, 16–23. (2012).
2. J. Chu, B. Indraratna, S. Yan, and C. Rujikiatkamjorn, “Overview of preloading methods for soil improvement.” *Proc. of the Insti. of Civ. Eng. – Gr.Impr.*, 167(3), 173–185. (2014).
3. W. Frikha, H. Zargayouna, S. Boussetta and M. Bouassida, M. “Experimental Study of Tunis Soft Soil Improved by Deep Mixing Column.” *Geotech. and Geo. Engi.*, 35(3), 931–947. (2017).
4. S.R. Kadhim, L. Parsons, and J. Han. *Stability Analysis of Embankments Supported by Geosynthetic Encased Stone Columns*. ASCE, 2318–2327 (2015)
5. S.Y. Liu, J. Han, D. W. Zhang, and Z. S. Hong.. *A Combined DJM-PVD Method for Soft Ground Improvement*. *Geosyn. Interna.* 15 (1): 43–54. (2008)

6. M. Benkhalifa, Z. Ben Salem, and W.Frikha “A new method of acceleration of consolidation using a cylindrical cavity expansion in presence of vertical drains.” *Mari. Geo.&Geotech.* (2022).
7. W.Frikha, M. Benkhalifa, Z. Bensalem."Methodemixed'acceleration de la consolidation des sols mous/Mixed method of accelerating consolidation of soft soils". Patent INORPI. (TN2019/135) Tunisia (2019).
8. Z. Ben Salem, W. Frikha and M. Bouassida “Effect of Granular-Column Installation on Excess Pore Pressure Variation during Soil Liquefaction.” *Interna. J. of Geome.*, 16(2), (2016).
9. B. Indraratna, C. Rujikiatkamjorn and I. Sathananthan “Radial consolidation of clay using compressibility indices and varying horizontal permeability”. *Cana. Geotech. J.* 42 1330-1341. (2005).
10. I. Sathananthan and B.Indraratna “Laboratory Evaluation of Smear Zone and Correlation between Permeability and Moisture Content. *J. of Geotech. and Geoenviron. Eng.*”, ASCE, 132(7), 942-945. (2006).