Analytical modeling and field assessment of embankment stabilized with vertical drains and vacuum preloading

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Analytical Modeling and Field Assessment of Embankment Stabilized with Vertical Drains and Vacuum Preloading

Modélisation Analytique et Évaluation de Terrain d'un Remblai stabilisé à l'aide de Drains Verticaux et de Préchargement par le Vide

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ABSTRACT: This study presents an analytical model of radial drainage with vacuum preloading using compressibility indices and varying horizontal permeability and considers the influence of linearly distributed vacuum pressure along the drain. An analytical solution based on the Cylindrical Cavity Expansion theory is used to evaluate the extent of the smear zone along the drain length and predict the performance of an embankment stabilized with vacuum-assisted prefabricated vertical drains at the New Bangkok International Airport (NBIA). Here, a significantly reduced height of sand surcharge could be applied because excess pore pressure was reduced by vacuum preloading. The performance of the embankment was evaluated under different vacuum pressure conditions during which the suction head could not be maintained in the field due to probable air leaks. In the analysis, therefore, the magnitude of applied vacuum pressure was based on field measurements and adjusted accordingly. The settlement predictions based on the writers' solutions were compared and agreed with the available field data. The results also indicate that the efficiency of the vertical drains depends on the extent of the smear zone, the magnitude and distribution of vacuum pressure and the extent of air leak protection provided in the field.

RÉSUMÉ : Cette étude présente un modèle analytique de système de drainage radial par préchargement par le vide utilisant des indices de compressibilité et une perméabilité horizontale variable et examine l'influence de la distribution linéaire de la pression de vide le long du drain. Une solution analytique basée sur la théorie d'Expansion de Cavité Cylindrique est utilisée pour évaluer l'étendue de la zone de souillure sur toute la longueur du drain et prédit la performance d'un remblai stabilisé à l'aide de drains verticaux préfabriqués sous vide sur le site du Nouvel Aéroport International de Bangkok (NBIA). Ici, on pourrait utiliser une hauteur de surcharge de sable considérablement réduite du fait que le préchargement par le vide a amoindri l'excédent de pression interstitielle. La performance du remblai a été évaluée sous différentes conditions de pression de vide pendant lesquelles la hauteur d'aspiration ne pouvait être maintenue sur le terrain à cause de probables fuites d'air. Dans l'analyse, le niveau de pression de vide appliquée était donc basé sur des mesures de terrain et était ajusté en conséquence. Les prédictions de tassement basées sur les solutions données par les auteurs ont été comparées aux données de terrain à notre disposition et ont été confirmées. Les résultats indiquent aussi que l'efficacité des drains dépend de l'étendue de la zone de souillure, de l'ampleur et de la distribution de la pression de vide, ainsi que de l'importance de la protection contre les fuites d'air disponible sur le site.

1 INTRODUCTION

A system of preloading with vertical drains is probably the most successful ground improvement technique available for low-lying soft clays where the objective is to accelerate consolidation by shortening the drainage path. The use of mandrel driven prefabricated (geosynthetics) vertical drain (PVD) with vacuum pressure is now economical. During installation, the surrounding soil is significantly remoulded near the mandrel where a zone of smear with reduced lateral permeability will be established: the extent of which can be determined by large-scale consolidation tests (Indraratna and Redana, 1998). Vacuum preloading was also used in the field to increase vertical drain performance. Negative pore pressure distributed along the drains and on the surface can further speed up consolidation, perform as an additional surcharge, and therefore the surcharge embankment height can be reduced to achieve the same degree of consolidation. The practical effects of the vacuum pressure has been discussed by Qian et al. (1992), Chu et al. (2000) and Indraratna et al. (2005a) among others, and the application of vacuum pressure with surcharge load but without any vertical drains was also modeled by Mohamedelhassan and Shang (2002).

This study presents a revised analytical model of radial drainage with vacuum preloading using compressibility indices and varying permeability coefficients. The Cylindrical Cavity Expansion theory used to analyse pile driving, tunneling and soil testing (Pestana et al., 2002), is also used to predict the extent of smear zone, based on the modified Cam-clay model (MCC). The influence of preconsolidation pressure, the magnitude of applied preloading and variation of soil compressibility and permeability are examined through the associated consolidation settlement. Finally, the settlement predictions at the centerline of the embankment are compared with field measurements taken from settlement plates.

2 SITE CONDITIONS

The proposed New Bangkok International Airport (Suvarnabhumi Airport) is located in the Samut Prakan Province near Bangkok. Located in lowland area the soft soil conditions are very problematic, so ground improvement techniques have to be designed and implemented to overcome potential problems related to soft ground, land subsidence and tight construction timelines. The fairly uniform sub-soil consists of a thin weathered clay crust (about 2.0 m thick) overlying soft Bangkok clay approximately 11 m thick. A stiff layer of clay lying beneath the soft clay extends 20-24 m below the surface while the ground water (piezometric surface) level is about 0.5m below the surface. The adopted parameters of subsoil layers determined by the Asian Institute of Technology are listed in Table 1 (AIT, 1995). Several test embankments were built on soft Bangkok clay, a few with vacuum preloading and PVDs. In this paper, the behaviour of selected embankment TV1 is analysed in detail. This embankment has a 40m × 40m base area and a side slope of 3:1; the vertical cross section is shown in Figure 1. The surface vegetation was removed and a 0.8m thick working platform was constructed with sand to serve as a drainage blanket. 50 mm diameter PVDs were installed by static or vibratory rigs at 1m spacing in a triangular pattern upto 15m deep. An air and water tight liner was placed on top of the drainage system with the liner edges atmospherically sealed at the borders of the embankment by a liner at the bottom of a 0.3m sand-bentonite trench. The embankment water collection system was connected to a vacuum pump capable of supplying continuous vacuum pressure for 3 months. A comprehensive instrumentation system to monitor the embankment behaviour including surface settlement plates, sub-surface multipoint extensometers, vibrating wire electrical piezometers and inclinometers were installed (Fig. 1).

Table. 1 Soil parameters used in the analysis

Depth m	C_r	C_c	k_h $\times 10^{-9}$ *m/s*	e_0	γ kN/m^3	P'_c *kPa*
0.0-2.0	0.06	0.37	30.1	1.8	16	58
2.0-8.5		1.6	12.7	2.8	15	45
8.5-10.5		1.7	6.02	2.4	15	70
10.5-13		0.95	2.56	1.8	16	80
13-15		0.88	0.60	1.2	18	90

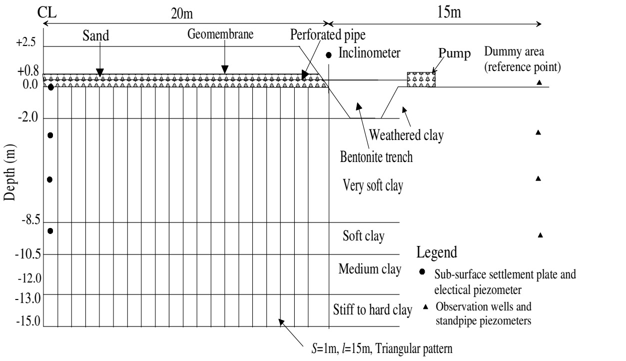

Figure 1. Vertical cross section of the test embankment with the subsoil profile, New Bangkok International Airport, Thailand (after Indraratna, et al., 2005b)

3 ANALYTICAL SOLUTIONS AND FIELD COMPARISONS

3.1 *Analytical solutions for vertical drain incorporating vacuum preloading considering compressibility indices and varying horizontal permeability*

In this section the analytical solution incorporating the compressibility indices (C_c or C_r) and varying horizontal permeability (k_h) for a unit cell is revised from the original theory developed by Indraratna et al. (2005b). Figure 2 illustrates the distribution pattern of vacuum pressure for an axisymmetric unit cell.

According to Indraratna et al. (2005b), the dissipation rate of average excess pore pressure ratio $(R_u = \bar{u}_t / \Delta p)$ at any time factor (T_h) can be expressed as:

$$\frac{\partial\left(R_u + \frac{p_0}{\Delta p}\frac{(1+k_1)}{2}\right)}{\partial T_h} = -\frac{8}{\mu}\frac{m_{vi}}{m_v}\frac{k_h}{k_{hi}}\left(R_u + \frac{p_0}{\Delta p}\frac{(1+k_1)}{2}\right) \qquad (1)$$

and $T_h = c_{hi}t/d_e^2$, $\mu \approx \ln(n/s) + (k_h/k_s)\ln(s) - 0.75$, $c_{hi} = k_{hi}/\gamma_w m_{vi}$, $n = d_e/d_w$, $s = d_s/d_w$

where,

c_{hi} = initial coefficient of consolidation for horizontal drainage
t = elapsed time
d_e = diameter of influenced zone
d_s = diameter of smear zone
d_w = diameter of vertical drain
k_h = average permeability coefficient in undisturbed zone
k_s = average permeability coefficient in smear zone
γ_w = unit weight of water
m_{vi} = initial coefficient of volume compressibility
p_0 = applied vacuum pressure at the top of the drain
k_1 = ratio between measured vacuum pressure at the top of the drain and the bottom of the drain
Δp = the applied preloading pressure

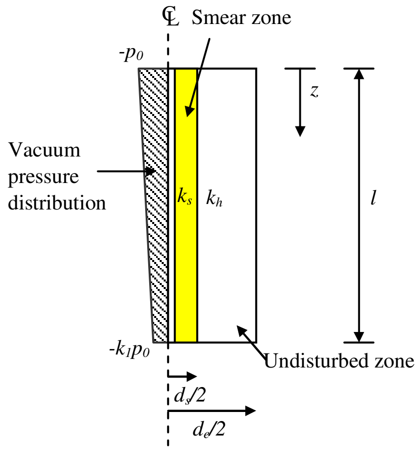

Figure 2. An axisymmetric unit cell with vacuum pressure distribution

The void ratio (e)-effective stress (σ') and the void ratio-permeability relations for normally consolidated clays can be express as (Tavenas et al., 1983):

$$\bar{e} = e_0 - C_c \log(\sigma'/\sigma'_i) \qquad (2)$$

$$\bar{e} = e_0 + C_k \log(k_h/k_{hi}) \qquad (3)$$

where, C_c is the compression index and C_k is the permeability index ($C_k \approx 0.5e_o$). If the current vertical effective stress (σ') is smaller than preconsolidation pressure (p'_c), the recompression index (C_r) is used instead of C_c for the overconsolidated range.

Differentiating Eq. (2) with respect to the effective stress (σ') gives:

$$m_{vi}/m_v = 1 + \Delta p/\sigma'_i - R_u \Delta p/\sigma'_i \qquad (4)$$

Combining Eqs. (3) and (4) gives:

$$k_h/k_{hi} = \left(1 + \Delta p/\sigma'_i - R_u\Delta p/\sigma'_i\right)^{-C_c/C_k} \qquad (5)$$

Substituting Eqs. (4) and (5) into (1) yields:

$$\partial\left(R_u + \frac{p_0}{\Delta p}\frac{(1+k_1)}{2}\right) \Big/ \partial T_h = -8P\left(R_u + p_0(1+k_1)/2\Delta p\right)/\mu \quad (6)$$

where, $P = \left(1 + \Delta p/\sigma'_i - R_u\Delta p/\sigma'_i\right)^{1-C_c/C_k}$

It can be seen that Eq. (6) is a non-linear partial differential equation for radial consolidation under instantaneous loading, incorporating the e-logσ' and e-logk_h relations. The nonlinear differential Eq. (6) with variable R_u does not have a general solution and, P varies between 1 and the value of $\left(1 + \Delta p/\sigma'_i + p_0(1+k_1)/2\sigma'_i\right)^{1-C_c/C_k}$. Hence, an average value is adopted P, given by:

$$P = P_{av} = 0.5\left[1 + \left(1 + \Delta p/\sigma'_i + p_0(1+k_1)/2\sigma'_i\right)^{1-C_c/C_k}\right] \quad (7)$$

Integrating Eq. (6) after incorporating Eq. (7) subjected to the boundary condition that R_u = 1.0 at T_h=0, gives the following algebraic expression:

$$R_u = \left(1 + \frac{p_0}{\Delta p}\frac{(1+k_1)}{2}\right)\exp\left(\frac{-8T_h^*}{\mu}\right) - \frac{p_0}{\Delta p}\frac{(1+k_1)}{2} \quad (8)$$

where, $T_h^* = P_{av}T_h$ (9)

When the value of C_c/C_k approaches unity and p_0 becomes zero, the writers' solution converges to the conventional solution proposed by Hansbo (1981):

$$R_u = \exp(-8T_h/\mu) \quad (10)$$

The average degree of radial consolidation (U_r) and the associated settlements (ρ) are evaluated by the following well-known equations:

$$U_r = 1 - R_u \quad (11)$$

$$\rho = \rho_c U_r \quad (12)$$

where, ρ_c is total primary consolidation settlement

3.2 *Prediction of smear zone radius ($d_s/2$) caused by mandrel driven vertical drains using the Cylindrical Cavity Expansion analysis*

When a mandrel is driven into soil it will initially displace a volume of soil equal to the volume of the mandrel. A heave of soil can occur at the surface up to ten times the mandrel radius (Hagerty and Peck, 1971). At a greater depth the soil is displaced radially, therefore, the expansion of a cylindrical cavity with a final radius equal to the mandrel will predict the extent of the smear zone. After initial yielding at the cavity wall, a zone of soil extending from the cavity wall to a radial distance (r_p) will become plastic as cavity pressure increases. For soil obeying the MCC model the yielding criterion is given by:

$$\eta = \mathrm{M}\sqrt{p'_c/p' - 1} \quad (13)$$

where, η = stress ratio q/p' (q is the deviatoric stress $(\sigma_1-\sigma_3)/2$ and p' is the effective mean stress $(\sigma'_1+2\sigma'_3)/3$, M = slope of critical state line projected to q-p' plane and p'_c = effective preconsolidation pressure. The stress ratio at the elasto-plastic boundary can be found as follows:

$$\eta_p = (q/p')_{r=r_p} = q_p/p'_0 = \mathrm{M}\sqrt{OCR - 1} \quad (14)$$

where, subscript p denotes the elasto-plastic boundary, r = the distance from the central axis of the drain and OCR is the isotropic over consolidation ratio.

Stress ratio at any point can be determined as follows:

$$\ln\left(1 - (a^2 - a_0^2)/r^2\right) = -2(1+\nu)\kappa\eta/3\sqrt{3}\upsilon(1-2\nu) - 2\sqrt{3}(\kappa\Lambda/\upsilon\mathrm{M})\ f(\mathrm{M},\eta,OCR) \quad (15)$$

and
$$f(\mathrm{M},\eta,OCR) = \frac{1}{2}\left[\frac{(\mathrm{M}+\eta)\left(1-\sqrt{OCR-1}\right)}{(\mathrm{M}-\eta)\left(1+\sqrt{OCR-1}\right)}\right] - \tan^{-1}(\eta/\mathrm{M}) + \tan^{-1}\left(\sqrt{OCR-1}\right) \quad (16)$$

where, a = radius of the cavity, a_0 = initial radius of the cavity, ν = Poisson's ratio, κ = slope of the overconsolidation line, υ = specific volume and $\Lambda = 1 - \kappa/\lambda$ (λ is the slope of the normal consolidation line). Finally, the corresponding mean effective stress, in terms of deviatoric stress, total stress and excess pore pressure, can be expressed by the following expressions:

$$p' = p'_0\left[OCR/\left(1 + (\eta/\mathrm{M})^2\right)\right]^{\Lambda} \quad (17)$$

$$q = \eta\, p' \quad (18)$$

$$p = \sigma_{rp} - q/\sqrt{3} + 2/\sqrt{3}\int_r^{r_p}(q/r)dr \quad (19)$$

Using Eqs. (17)-(19), the excess pore pressure (Δu) due to mandrel driving can be determined by:

$$\Delta u = (p - p_0) - (p' - p'_0) \quad (20)$$

where, p_0 = initial total mean stress.

The extent of the smear zone is the region in which excess pore pressure is higher than the initial overburden pressure (σ'_{v0}) because, in this region, the soil properties such as permeability and soil anisotropy are radially disturbed to give $\Delta u \geq \sigma'_{v0}$. The predicted smear zone based on soil parameters (Table 1) is shown by Fig. 3 at 14-15m deep. Figure 4 illustrates the variations of smear zone with depth as predicted by the proposed solution.

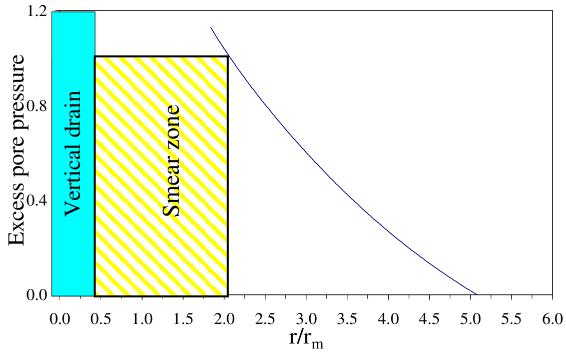

Figure 3. Smear zone prediction using Cavity expansion analysis down to 14-15m depth (where, r_m is the equivalent radius of mandrel)

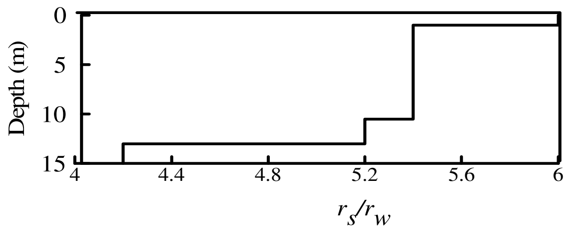

Figure 4. Variation of smear zone with depth by the Cavity Expansion theory (where, r_s: radius of smear zone, and r_w: radius of drain)

3.3 *Stage construction and vacuum pressure measurements*

A vacuum pump capable of generating 70kPa was used and after 45 days of vacuum application, the embankment was raised in 4 stages to a height of 2.5 m (the unit weight of surcharge fill was 18 kN/m^3). The loading stages of the embankment are illustrated in Fig. 5.

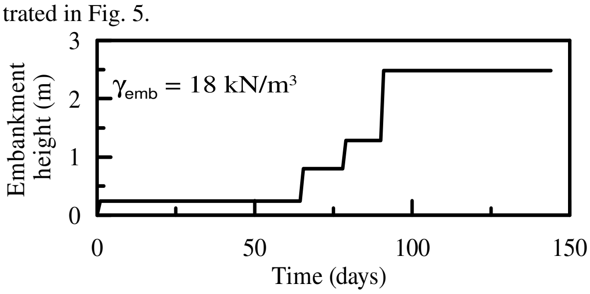

Figure 5. Construction loading history of embankment

Figure 6 illustrates pore pressure measured at various depths by vibrating wire piezometers. The suction head observed in the field was lower after 40 days, and also decreased down the length of vertical drains. The lower suction head at the surface may be attributed to probable air leaks therefore the assumed vacuum pressure value at the surface was adjusted in the analysis based on field measurements (Fig. 6). It was also assumed the vacuum pressure was zero at the bottom of the drains (i.e. k_l=0). Based on previous experience (Indraratna et al., 2005b), the permeability ratio between the undisturbed and disturbed zone (k_h/k_s) was set at 10.

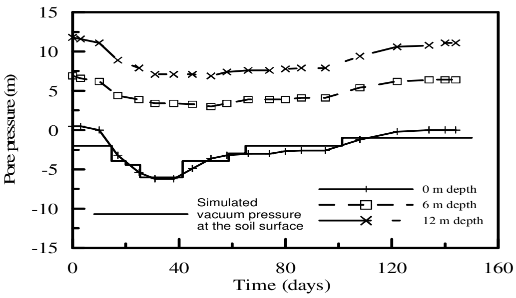

Figure 6. Pore pressure of embankment at various depths and assumed vacuum pressure at the surface applied in the analysis

3.4 *Simulation of vacuum consolidation*

Variation of smear zone and the consolidation settlements at the centreline were calculated using Eqs. (8)-(12) and (20). The computation of the consolidation settlement follows 1-D consolidation theory and is readily calculated using aspread-sheet . The value of the soil compressibility index (C_c or C_r) is associated with the actual stress state within a given region of the foundation especially in the weathered crust (Indraratna and Redana, 2000).

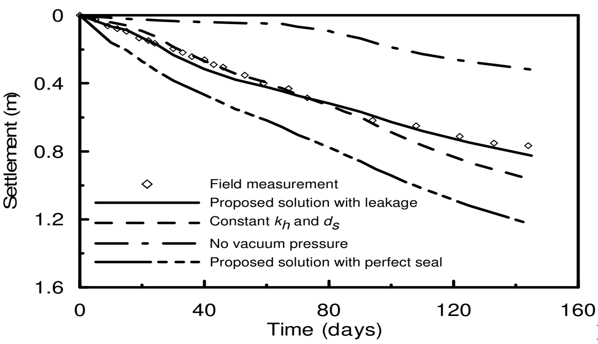

Figure 7. Surface settlement predictions at Embankment TV1

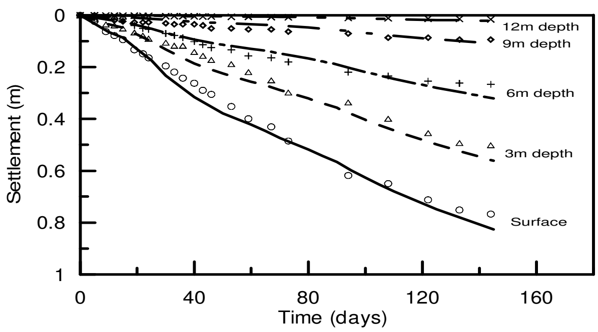

Figure 8. Consolidation settlements at various depths

Figure 7 compares predicted surface centreline settlement with the measured data, while Fig. 8 compares predicted sub-surface settlements with measured data by the proposed solutions. As expected, the predicted results based on the writers' solutions agree well with the measured results even at greater depths, whereas the prediction based on the constant k_h and smear zone overestimates settlement after 80 days, because, the actual soil permeability decreases significantly at higher stress levels. It was verified that the combined vacuum application and the PVD system accelerates the consolidation, while the vacuum pressure acts as an additional surcharge load. As shown in Fig. 7, a perfect seal gives more settlements but its efficiency depends entirely on preventing airleaks and the distribution of vacuum pressure along the length of the drain.

4 CONCLUSIONS

A revised analytical model for vertical drains incorporating vacuum preloading and smear effect using compressibility indices and varying horizontal permeability for simulating radial consolidation around PVD has been developed. The extent of the smear zone caused by driving the mandrel was based on the Cylindrical Cavity Expansion theory incorporating the modified Cam-clay model. Variations of smear zone and vacuum pressure along the vertical drains were considered in the case history analysis: the results indicated that predictive accuracy is governed by correctly assuming the vacuum pressure distribution and the extent of the smear zone. Within these limitations, the proposed solutions indicate an improved predictive accuracy in field measurements. It can also be concluded that a PVD system subjected to vacuum preloading will only be effective as long as the potential air leaks can be minimised in the field.

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