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Predicting Deformations in Vacuum Assisted Ground Improvements Using an Elasto-Viscoplastic Numerical Model

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Abstract. Vacuum consolidation can be used to accelerate the soil consolidation in ground improvement projects. Capped Prefabricated vertical drains (CPVDs) is an improved method where vacuum is applied to each PVD separately. This is particularly useful if the area is inundated or have a high permeable sand layer or seam. Vacuum consolidation in an actual project is much challenging to model and predict the performance. This is due to the switching on and off of the vacuum pump, accidental failures of the pump etc. in the field and they need to be incorporated in the analysis. In this paper an elasto-viscoplastic (EVP) model, capable to simulate such instances, is presented and is validated against a field case reported from a land reclamation project in Singapore.

Keywords. Geosynthetics, creep, vacuum consolidation.

1. Introduction

Application of vacuum suction to soft clay ground improvements generally results in faster rate of consolidation [1]. Vacuum increases the hydraulic gradient towards the PVDs which in turn accelerates the dissipation of excess pore pressure underneath the foundation soil resulting in faster consolidation. Although the first trial to use vacuum was done long ago by Kjellman (1952) [2], practical application was rather limited until the advancement in geosynthetics technology. Recent developments with geosynthetics and construction methods have enabled vacuum suction to be applied more efficiently via prefabricated vertical drains (PVDs) to deep soft clay layers, making vacuum assisted consolidation a successful method of ground improvement.

There are two main methods in practice in applying vacuum suction to the foundation soil. Namely, the membrane and membraneless methods. The membrane method uses a sealing blanket under which vacuum is applied. The membraneless method, on the other hand, uses pipes running to each PVD without essentially using a sealing membrane. The membraneless method has several advantages over the former. It is less susceptible to leakages; in case of high permeable sand layers or seams exists overlying soft clay, a pipe can be driven through the sand layer and vacuum can be applied directly to the clay layer. This method also permits unaffected functioning in

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case of groundwater fluctuations. However, time-consuming extensive tubing and associated cost is the main disadvantage of this system [3].

Numerical modelling of vacuum consolidation had been done using different methods. Treating vacuum as an equivalent vertical stress [4], modifying and using an equivalent permeability [5], modifying the boundary condition of the PVD [6] are such methods. Out of them, modifying the boundary condition method is extremely useful if the vacuum suction change over time and depth. The case study examined in this paper had a vacuum pump failure which can be conveniently modelled using the above approach.

2. EVP model for vacuum consolidation

A summary and salient features of the model are presented in the following sections. Further details of the model can be found elsewhere in Kumarage and Gnanendran (2019) [6].

2.1. Simulating the effect of vacuum

Mean effective stress (p') is defined as follows,

$$p' = \begin{cases} p - (-p_{vac}) \\ p - u \end{cases} \tag{1}$$

Generally, p' is defined as the difference between the total mean stress (p) and excess pore pressure (u). If conventional preloading is done with PVDs, it is safe to assume there will be no excess pore pressure along the PVD; hence $u = 0$. When vacuum is applied, along the PVD, $u = -p_{vac}$. p_{vac} can be considered as a constant in its most simplified form. It also can be considered as a function of time and depth as illustrated by Kumarage and Gnanendran (2018a) [8]. In the event of a vacuum pump failure or disturbance, the purpose written subroutine for the analysis can be called to switch the vacuum suction off or adjusted (see Kumarage and Gnanendran, 2019 [6] for further details). This feature has been useful since the project of interest, analysed in this paper had such vacuum pump failure during the consolidation time.

2.2. Secondary compression index (C_α)

Vacuum consolidation is often applied to soft clays and they generally undergo creep deformations. The question would be whether these creep deformations are significant so that they should be incorporated into predictions. The ratio $(\lambda - \kappa)/\alpha$ can be used as an indicator for assessing the suitability of a creep based model; where λ is the gradient of the normal consolidation line, κ is the gradient of swelling line and α is the secondary compression index in the natural log scale. If $(\lambda - \kappa)/\alpha < 25$, generally creep should not be ignored and vice versa [9]. If secondary compression data are not readily available, the ratio of $C_\alpha / C_c = 0.04 \pm 0.01$ [10] can be used as an approximation, where C_c is the slope of the virgin compression line. C_α can either be treated as a constant or as a variable of stress in the model.

2.3. Volumetric strain rates

Adopting to Perzyna (1963) [11] formulation, total volumetric strain rate $(\dot{\varepsilon}_{ij})$ is decomposed into two parts as in the Eq. (2),

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{e} + \dot{\varepsilon}_{ij}^{vp} \tag{2}$$

where $\dot{\varepsilon}_{ij}^{e}$ is the elastic strain rate and $\dot{\varepsilon}_{ij}^{vp}$ is the viscoplastic strain rate. $\dot{\varepsilon}_{ij}^{e}$ is calculated according to generalised Hooke's law and $\dot{\varepsilon}_{ij}^{vp}$ is calculated as per the Eq. (3),

$$\dot{\varepsilon}_{ij}^{vp} = \langle \phi \rangle \frac{\partial f}{\partial \sigma'_{ij}} \tag{3}$$

where ϕ is the rate sensitivity function defined in Eq. (4), f is the function for the loading surface and σ'_{ij} is the effective stress.

$$\phi = \frac{\alpha}{\bar{t} v_0} \left(\frac{p_L}{\bar{p}_0} \right)^{\frac{\lambda - \kappa}{\alpha}} \frac{1}{2\bar{p}_0 \left(\frac{1}{\xi} - \frac{1}{R} \right)} \tag{4}$$

where $\bar{t}$ is the reference time; v_0 is the specific volume; p_L and $\bar{p}_0$ are the intersections of the f and $\bar{f}$ (reference) surfaces with positive p axis; ξ is the stress ratio and R is the shape function. In the calculation, firstly ϕ should be determined. Then the determination of $\dot{\varepsilon}_{ij}^{vp}$ and $\dot{\varepsilon}_{ij}$ should follow.

3. Field trial on reclamation site in Singapore

Singapore has adopted land reclamation as the key strategy to increase its land mass [12], [13]. Main challenges had been the scarcity of fill material and the reclamation works moving towards deeper water. In such a setting, vacuum consolidation with Capped PVDs would be the most economical method of ground improvement.

Reclamation site discussed in this paper had mainly three soil layers [12]. The soft clay layer has been sandwiched from a silty sand layer placed in 2001 from the top and a siltstone layer from the bottom. Thickness of these layers varied significantly over the treated trial area of 100 m by 50 m (Figure 1a). Figure 1b shows the instrumentation of the reclamation site. BH-1 location had the highest thickness of soft clay and is in the mid-section of the area. Hence it was selected for the analysis reported in this paper.

4. Finite Element implementation

AFENA [7] modified version for vacuum consolidation in UNSW Canberra was used for the analysis. EVP model described above was used to model the sandwiched soft clay layer. Biot type Mohr-Coulomb consolidation elements were used for the top and bottom sandy layers.

The top silty sand layer had been laid in 2011 but there was no data to confirm the degree of consolidation that the soft clay has undergone so far due to this layer. For the convenience in modelling, it was assumed that the primary consolidation has finished and therefore no excess pore pressure exists in the soft clay due to this layer.

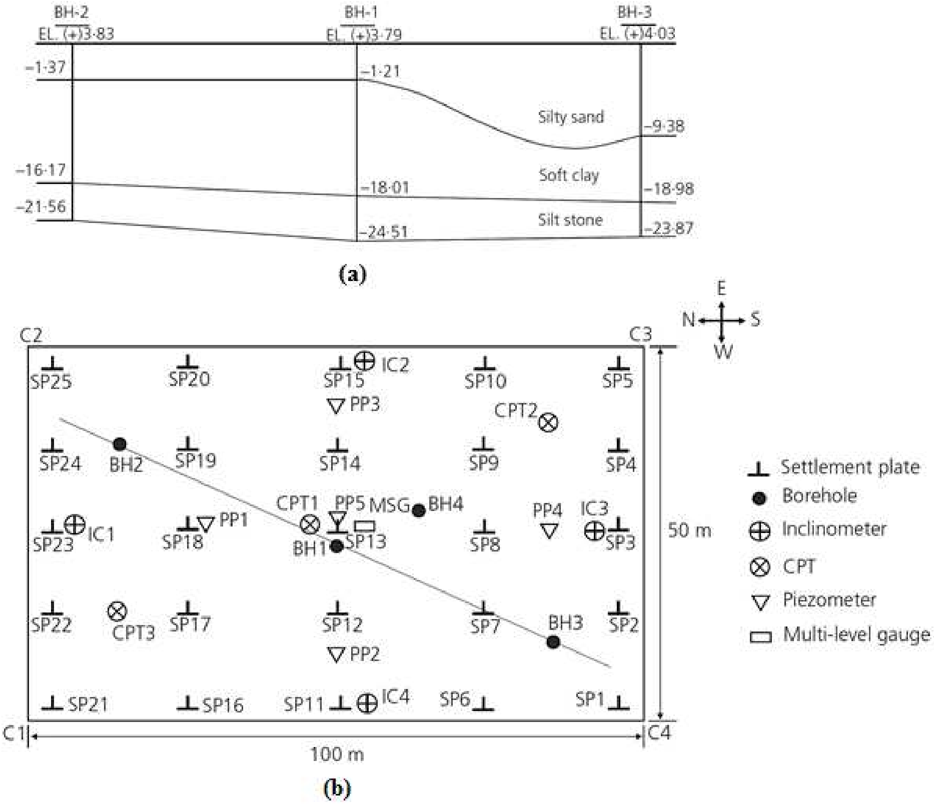

Figure 1. Instrumentation of the field trial site (modified from Lam et al. 2018).

C_α for the soft clay layer was approximated using the ratio proposed by Mesri and Godlewski (1977) [10] and the maximum and minimum values of C_α calculated was 0.031 and 0.019 respectively. An average permeability of 3×10^{-10} m/s was adopted for the soft clay layer. Properties of the unit cell adopted for the finite element analysis (FEA) are displayed in Table 2.

Table 1. Material properties for the FE analysis.

Material	Depth (m)	M	κ	λ	e_0	γ_{sat}	K_0	OCR
Silty Sand	0 to 5	*E=10,000 ; ν=0.3 ; φ'=32*				17.0	0.50	1.0
Soft Clay	5 to 21	1.113	0.034	0.27	1.9	15.4	0.47	1.0
Silt Stone	21 to 28.3	*E=10,000 ; ν=0.3 ; φ'=32*				15.8	0.67	2.0

Table 2. Properties of the unit cell.

Property	Value
PVD Spacing	1 m
Pattern	Triangular
r_w (well radius)	0.03 m
r_s (smear zone)	0.12 m
R_e (equivalent radius of the PVD)	0.525 m

4.1. Vacuum application and embankment construction

Vacuum suction was applied four weeks prior to the commencement of embankment filling. The embankment was raised to 2.5 m high in 25 days. The density of filling material was 20 kN/m^3 hence the total stress acted upon the foundation soil was 50 kPa. In the unit cell analysis, this stress was applied as a traction to the surface of the unit cell.

Vacuum pump was not stable between 80th and 150th days. As mentioned earlier, the modified AFENA program has the capability of switching vacuum on and off and also to adjust the intensity of vacuum as necessary. Hence this capability was used to call the relevant subroutine in the program to switch off and back on the vacuum in the respective time period.

Switching on and off the vacuum pump makes an immediate change in the boundary condition which can result numerical instability. This has been illustrated previously by Kumarage and Gnanendran (2018b) [14]. To ensure convergence, either very small time steps (0.001 days) or few iterations using Newton Rapson method was necessary.

5. Results and synthesis

Figure 2 shows the comparison between the field data and FEA predictions of settlement and excess pore pressure. Settlement data are from the BH1 location where highest clay thickness was found and excess pore pressure data are from PP5 location near BH-1 location. From Figure 2-a, it appears that the numerical model captures the soil settlement behaviour well. Some retardation in settlement can be observed from 80 to 150 days due to the vacuum pump failure.

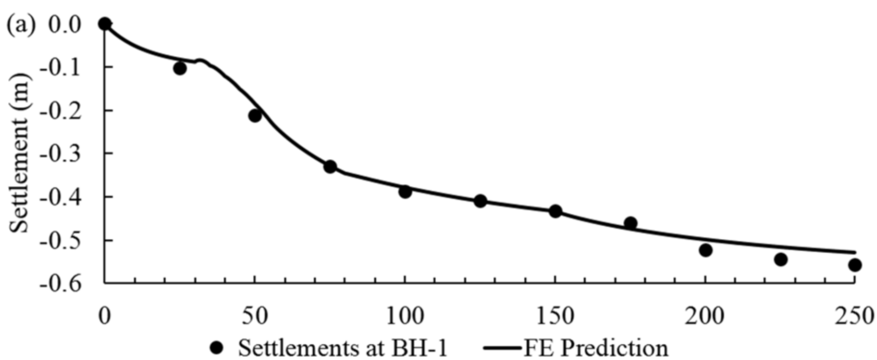

Figure 2. Settlements and Excess pore pressure data against FE predictions.

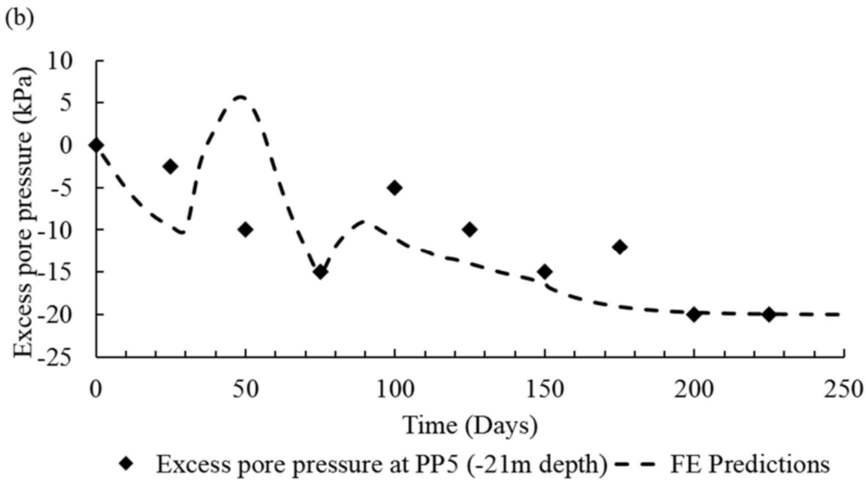

Figure 2. (*continued*) Settlements and Excess pore pressure data against FE predictions.

Excess pore pressure predictions have some deviations from the field measurements (Figure 2-b). Increase in excess pore pressure due to embankment construction is not so obvious. This could be due to the high permeable sandy soil layers that exit above the top and below the soft clay layer. Also, there are some fluctuations in the field data around 170 days. It is reported that the area had some rainfall during the ground improvement project, but data concerning the fluctuations in the water table was not available [12]; hence they could not be incorporated in the model. This change in water table could be another reason for the deviation. Increase in excess pore pressure due to vacuum pump failure can be observed in both field data and FEA predictions during 80th to 150th days. Considering these uncertainties and challenges, the settlement and excess pore pressure predictions from the FEA using the EVP model appear reasonably good.

6. Summary and concluding remarks

An elastic-viscoplastic model has been presented in this paper which is capable in modelling vacuum consolidation. It has been shown that practical problems such as failures in vacuum pump can be successfully modelled using the boundary value modification method. Since creep data was not readily available, they were approximated using the C_α / C_c ratio proposed by Mesri and Godlewski (1977) [10] and this appears to give reasonably good settlement and excess pore pressure predictions from the FEA using the EVP model discussed in this paper.

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