Creep based viscoplastic numerical modelling of soil deformations in vacuum application and removal

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ABSTRACT
With recent research on test embankment case studies and laboratory experiments, it is evident that vacuum consolidation can be effectively used to reduce long-term settlements in soft soil by taking the soil to an overconsolidated state with vacuum application and subsequent removal. Settlement characteristics during vacuum consolidation and swelling characteristics after removal of vacuum have found to be different, which needs careful attention in modelling. In this paper, a fully coupled Biot type elasto-viscoplastic (EVP) model is proposed to predict both excess pore pressures and settlements more accurately upon application and removal of vacuum. In addition, the effect of the duration of vacuum application and removal secondary compression is also discussed.
Keywords: Creep, Vacuum Consolidation, Over-consolidation

RÉSUMÉ
Avec des recherches récentes sur des études de cas de remblai et des expériences en laboratoire, il est évident que la consolidation sous vide peut être utilisée efficacement pour réduire les tassements à long terme dans un sol meuble en soumettant le sol à un état surconsolidé. Les caractéristiques de sédimentation lors de la consolidation sous vide et les caractéristiques de gonflement après l'élimination du vide se sont révélées différentes, ce qui nécessite une attention particulière dans la modélisation. Dans cet article, un modèle élasto-viscoplastique (EVP) de type Biot entièrement couplé est proposé pour prédire plus précisément les pressions interstitielles et les tassements en excès lors de l'application et de l'élimination du vide. En outre, l'effet de la durée de l'application du vide et de l'élimination de la compression secondaire est également discuté.
Mots-clés: Fluage, Consolidation sous vide, Sur-consolidation

1 INTRODUCTION

Ground improvement with prefabricated vertical drains (PVDs) coupled with vacuum suction has been getting increasingly popular in the last decade due to its ability to accelerate consolidation process compared to conventional preloading. Vacuum consolidation is claimed to be an economical ground improvement method especially in applications with deep soft clay layers (Yan and Chu, 2003). Effect of vacuum consolidation is often idealized and explained using the spring mechanism used for the consolidation. However, vacuum consolidation is different from surcharge in few different ways.

Vacuum application can accelerate inward radial drainage by increasing the hydraulic gradient towards the vertical drain. For naturally deposited soils, horizontal permeability is generally higher than of vertical permeability. Hence vacuum application has compounded advantages in accelerating consolidation. Vacuum application can reduce outward lateral displacements caused by the construction of embankment and hence faster rate of embankment building is possible.

It has been confirmed that the application and removal of vacuum can yield higher over consolidation ratio (OCR) than fill surcharge alone (Kianfar et al., 2015) (Figure 1). As reported previously by Fukazawa et al. (1994), OCR has direct effect on secondary compression. Hence, achieving higher OCR helps to minimize long-term deformations by reducing the secondary compression.

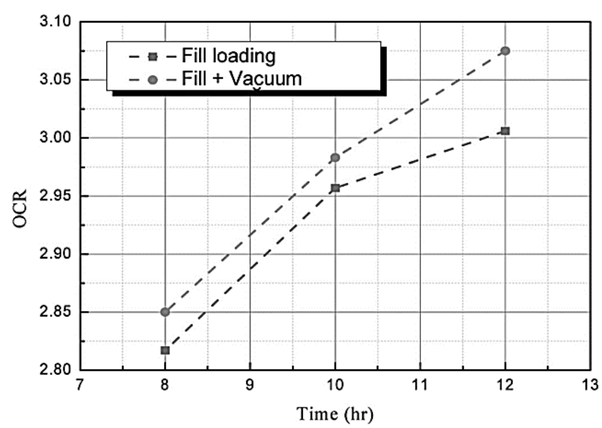

Figure 1: OCR with and without vacuum (Kianfar et al., 2015)

In this paper a creep based viscoplastic model is extended to predict vacuum application and removal. The difficulty in predicting swelling characteristics and transition to over consolidated state in vacuum removal is overcome.

Application of viscoplastic models and its ability to predict long term deformations in vacuum consolidation has been discussed previously by Kumarage and Gnanendran (2017). However, in the said approach the ability of the model to predict the swelling characteristics after removal of surcharge or vacuum was not addressed and it is the main objective of this paper.

2 SALIENT FEATURES OF THE MODEL

Viscoplastic volumetric strains in clay under vacuum assisted consolidation are given by Eq.[1]

$$\dot{\varepsilon}_{vol}^{vp} = \frac{\alpha}{\bar{t}\,(1+e_0)}\left(\frac{p_{sur}+p_{vac}}{\bar{p}_0}\right)^{\frac{\lambda-\kappa}{\alpha}} \quad [1]$$

where α = secondary compression index in natural logarithm axis, $\bar{t}$ = reference time, e_0 = initial void ratio, p_{sur} = mean stresses due to surcharge, p_{vac} = mean stresses due to vacuum, $\bar{p}_0$ = size of the yield surface, λ = slope of the virgin compression line and κ = slope of the recompression line in natural log axis.

Secondary compression is generalised depending on the current stress state following Nash (2001) as per Eq. [2]

$$\frac{C_\alpha}{C_{\alpha i-1}} = \left(\frac{p_i}{p_{i-1}}\right)^{\frac{\lambda-\kappa}{\alpha-i}} \quad [2]$$

where C_α = current value of secondary compression, p_i = current stress state, The subscript α*-1* indicates the respective values in the previous stress state.

2.1 Deformation after releasing vacuum and surcharge

To improve the predictions in the swelling phase, in this paper, volumetric deformations during swelling are multiplied by a correction factor β such that,

$$\dot{\varepsilon}_v^* = \beta \times \dot{\varepsilon}_v \quad [3]$$

where $\dot{\varepsilon}_v^*$ = corrected volumetric strain rate, $\dot{\varepsilon}_v$ = volumetric strain rate during swelling, β = correction factor during swelling.

Chai et al. (2005) proposed to use and vary the correction factor depending on the K_0 (K_0 = horizontal earth pressure coefficient at rest) condition of the soil. In field cases, in the presence of vacuum, K_0 condition can change with the depth and may not prevail in shallow depths. This check can be made by defining the stress ratio (K) such that,

$$K = \frac{\sigma_{vac}}{\sigma_{vac}+\sigma'_v} \quad [4]$$

where σ_{vac} = vacuum suction and σ'_V = vertical stress applied. If $K \leq K_0$ it can be considered that K_o condition prevails and vice versa (Chai et al. 2005, Robinson et al. 2012). However, in laboratory samples, it is reasonable to assume a similar K or K_0 condition along the entire height of the sample due to the small size. In the subsequent validation, it was determined that K_0 condition prevails throughout the experiment.

3 VALIDATION AGAINST EXPERIMENTAL DATA

Radial consolidation response of 150 mm diameter size Kaolin clay reported by (Kianfar et al., 2015) is used to validate the proposed methodology. Properties of the clay adopted for the validation are displayed in following table.

Table 1: Kaolin Clay properties (Modified from Kianfar et al., 2013)

Property	Value
Slope of the consolidation line : λ	0.17
Slope of the swelling line : κ	0.03
e_N[1]	1.85
Friction angle: φ'	27^0
Slope of the critical state line: M	1.07
Secondary compression: C_α (Assumed)[2]	0.0117

[1] Void ratio in normal consolidation line at ***p'=1***
[2] Assumed that C_α/C_c=0.03 which represents the lowest ratio proposed by Mesri and Godlewski (1977).

Vacuum has been applied with a small 14.5 mm diameter drain casted at the centre of the consolidation cell. In Finite Element (FE) modelling this boundary condition was modified to simulate vacuum suction. Two tests are validated here, both with a surcharge and vacuum each being 50 kPa.

- Test A: Surcharge (50 kPa) and Vacuum (50 kPa) applied. Vacuum removed after 8 hours and surcharge removed after 72 hours.
- Test B: Surcharge (50 kPa) and Vacuum (50 kPa) applied. Vacuum removed after 12 hours and surcharge removed after 72 hours.

Both tests ran up to 144 hours. Their excess pore water pressure (EPWP) responses and strains are predicted and displayed in Figure 2.

It appears that the EPWP predictions have a good agreement with the measured data. It was experienced that the instantaneous change in boundary conditions (such as removal of vacuum) can yield convergence problems with the EVP model. In such instances, few iterations using Newton Rapson (NR) method could converge to the solution. However, when the FE mesh becomes larger, NR method can be less efficient. In addition, it was identified that, instead of instantaneous change in boundary conditions (to represent vacuum removal), if it is done over a few time increments, solution divergence can conveniently be prevented. However this would introduce

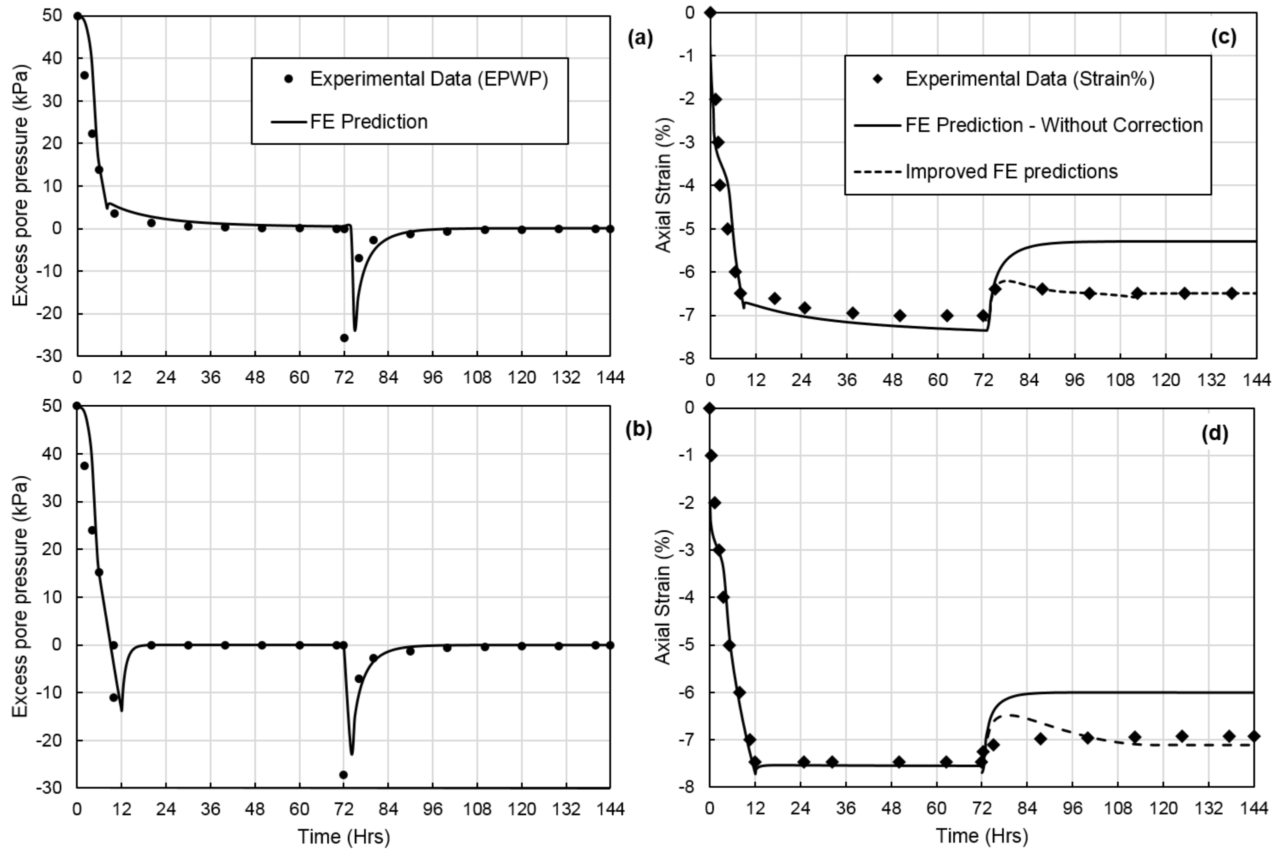

Figure 2: (a) Excess pore pressure response- Test A; (b) Excess pore pressure response- Test B; (c) Strain with time% - Test A; (d) Strain % with time - Test B.

an offset of FE predictions against experimental data as evident from Figure 2 (a) and (b) at the time of vacuum and surcharge removal.

Regarding vertical strain predictions, final swelling after removing both surcharge and vacuum has been over estimated by 1% of the axial strain. In laboratory experiments, this can be due to the side wall friction. But careful investigation on this phenomenon has revealed that provided the friction and experimental errors are small, predictions of final settlements and swelling are still challenging in vacuum consolidation (Chai et al. 2005, Wu et al. 2016).

The correction applied in swelling phase has significantly improved the prediction as illustrated by Figure 2 (c) and (d). However, as the applied vacuum duration increases, more deviations arise from the experimental data.

The correction factor β in this case was approximately 0.82. This has close agreement with the minimum correction proposed by Chai et al. (2005) for axisymmetric condition, which is 0.80. As per Figure 2-(d), once vacuum duration becomes longer, predictions seem to deviate during the instantaneous swelling phase. Once swelling phase is over (e.g. after 120 hours), FE prediction are closely matching with experimental data.

4 SENSITIVITY ANALYSIS ON VACUUM DURATION FOR REDUCING LONG TERM SETTLEMENTS

Duration of the vacuum application is a common problem an engineer may face in vacuum consolidation projects. It is generally considered that higher duration of vacuum application can reduce the post construction settlements. Kosaka et al. (2016) have made field observations on applying vacuum to reduce secondary compression. However, the duration of the vacuum application is often bounded by economic factors such as the cost of running the vacuum pump.

To illustrate the EVP response for the duration of vacuum application, a sensitivity analysis was carried out on Ballina clay. Five scenarios have been simulated varying the duration of the vacuum application as illustrated in Table 2. Soil parameters used for the analysis are in Table 3. These parameters attribute to Ballina clay, approximately at 10 m depth and was adopted from Pineda et al. (2016). A unit cell with a height of 10 m and 0.5 m radius was discretised with 6-noded triangular elements for the FE mesh.

Loading of 70 kPa was applied to the top most elements of the mesh, and surface settlements were monitored. EPWP was monitored at the outer most element at the mid

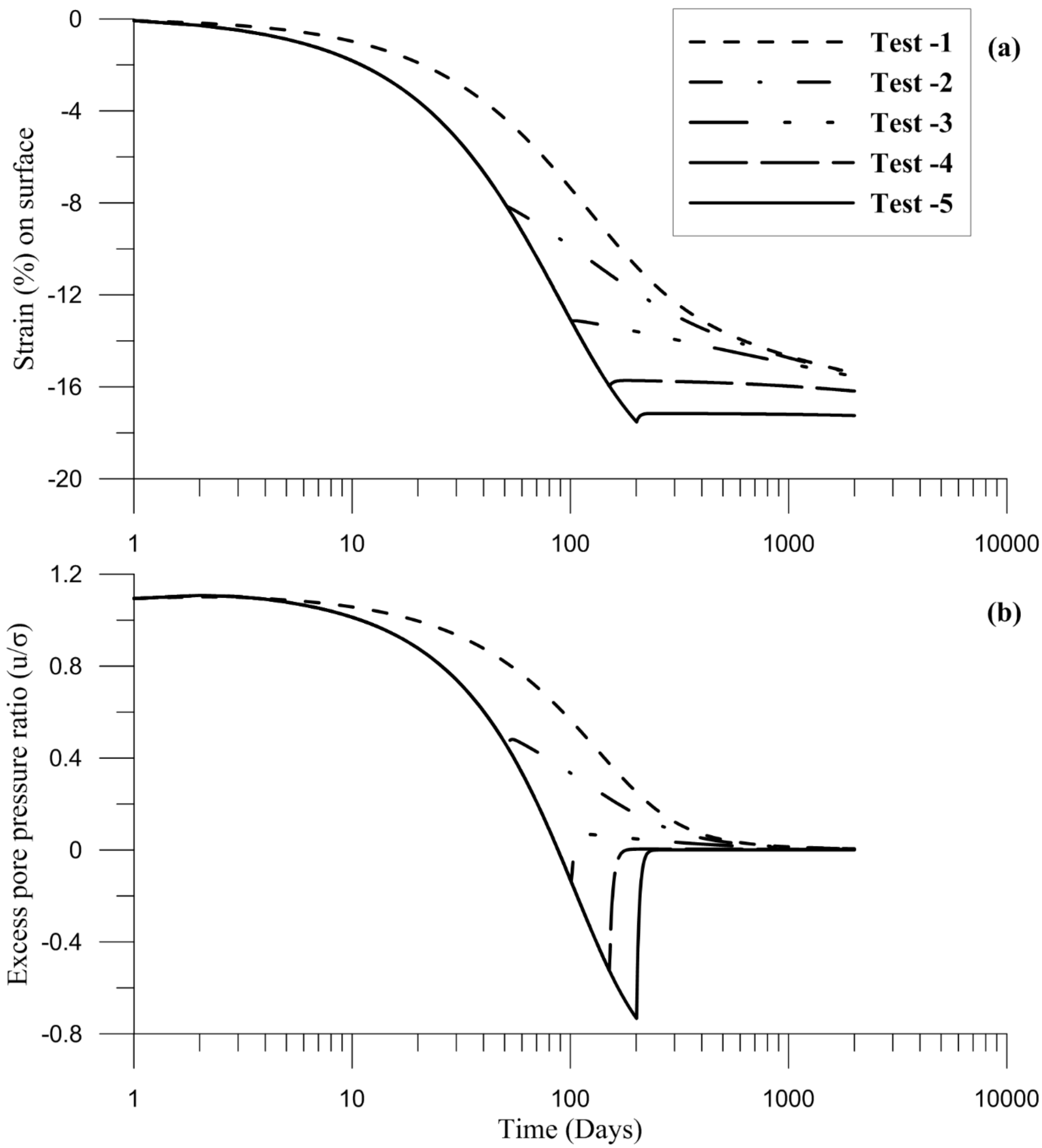

Figure 3: Effect on vacuum duration; (a) Vertical Strain %; (b) Excess pore pressure

Table 2: Summary of test details for the sensitivity analysis

Test	Vacuum duration (Days)
1	No Vacuum
2	50
3	100
4	150
5	200

depth (i.e 5 m). Outer edge was chosen since it indicates the halfway between the drains in the field and for the same reason it can show the maximum values of EPWP.

As illustrated in Figure 3-(b), after 800 days EPWP has been almost dissipated in all five tests. Test no.1 without vacuum, has taken around 800 days to dissipate EPWP completely. Application of vacuum could accelerate the process and has reduced the EPWP to zero in around 100 days. After approximately 800 days since the there is no significant EPWP, and vacuum being switch off, settlements are primarily governed by secondary compression.

The slope of the time-strain curve after 800 days in gives an idea about the secondary compression taking place in this duration. It is clear that by application of vacuum for a longer period, slope of the time-strain curve get significantly reduced. Reduction in secondary compression is significant when vacuum keeps applied until EPWP becomes negative. Soil swelling can also be observed at his stage. Application of vacuum for sufficient duration can bring the soil in to an overconsolidated state and thereby reduce the coefficient of secondary compression.

Table 3: Soil parameters adopted for the sensitivity analysis

Parameter	Value
M	1.5148
λ	0.525
κ	0.0525
e_0	2.80
C_α	0.057
K_h(m/s)*10^{-10}	9.38
p'_c (kPa)	60

Reduction of coefficient of secondary compression with the over consolidation ratio (OCR) has also been discussed by Fukazawa et al. (1994) with respect to conventional soil improvements. The soil rebound observed in Test No. 4 and 5 in Figure 3 is an indication of the overconsolidated soil being swelled upon removing the vacuum.

Generally it is convenient to monitor the EPWP than settlements, since the engineer can clearly identify the time EPWP becomes zero. With this sensitivity analysis, it is clear that running the vacuum pump after EPWP becomes zero, will swell the soil upon removing the vacuum suction. Observing the EPWP and running the vacuum pump until the desired degree of consolidation (based on EPWP) or OCR is achieved, is important to reduce long-term post construction settlements. Bringing the soil to an over consolidated state by application of vacuum can significantly reduce the creep deformations as illustrated from this sensitivity analysis.

5 SUMMARY AND CONCLUDING REMARKS

A creep based viscoplastic model for vacuum application and removal has been discussed in this paper. Pore pressure responses were satisfactorily predicted by the model. A correction was required with EVP models to predict soil swelling after removal of vacuum. The correction factor β was approximately 0.82 in this selected case. With increased vacuum suction and duration, it appears that further insight is necessary to generalise this approach. The proposed EVP model, with a variable creep index modelled as a function sensitive to OCR is found to be capable of modelling different long-term settlement and swelling behaviours with the application and removal of vacuum.

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