Numerical modelling of vacuum suction distribution and its effects in ground improvement with PVD vacuum consolidation

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ABSTRACT: Prefabricated vertical drains (PVDs) with vacuum suction have helped to shorten the consolidation time significantly in ground improvement projects. This method is claimed to be more effective and economical in consolidating deep soft clay layers. However, recent research has shown that the vacuum suction applied to PVD near the ground surface may not penetrate the full depth (i.e. along the full length) of the PVD and the actual effects of the vacuum suction on the consolidation of the clay are not clearly understood. In this paper, an innovative approach is presented to model the vacuum suction distribution along the PVD using Finite Element (FE) modelling. Complex vacuum distributions, close to elliptical in shape is modelled and validated against field performance monitoring data. Moreover, the effects of this vacuum distribution on the deformational behaviour of the soft clay are also discussed.

Keywords: Vacuum consolidation, Prefabricated Vertical Drains, Creep

1 INTRODUCTION

There are two methods to apply vacuum suction in vacuum consolidation ground improvements. These are commonly known as membrane and membrane-less methods. In the membrane method, an airtight sheet or membrane is placed on the ground surface and the vacuum is applied via PVDs that are installed below the membrane. Vacuum suction then travels along the PVDs to deeper levels of the ground. In membrane-less method, vacuum suction is applied to individual PVDs using the clayey soil as the sealing layer. This method is also knows as Capped-PVD or CPVD method, since vacuum lines are connected to each PVD using a geosythetic cap (Chai et al. 2010).

In both of the above methods, vacuum suction may not penetrate equally to the full depth of the PVD. Imperfections in the PVD, power limitations in the vacuum pump or sandwiched sand layers can be main causes for such vacuum loss. Recent development with geosynthetic technology such as developing CPVDs has allowed vacuum suction to be applied to individual PVDs resulting more effective application of vacuum. However, certain percentage of vacuum loss is still inevitable.

Several researches have reported vacuum suction getting lost along the depth of the PVD both in laboratory experiments and in field cases (e.g. Chai et al. 2006, 2008; Indraratna et al. 2004). This was noted both from low strain rate at deeper depths such as that reported by Indraratna et al. (2012) and inferred from changes of soil index properties after vacuum consolidation (e.g. Chu et al. 2000). Observations such as these made the researches to study this phenomenon further.

In modelling vacuum suction, initially a constant vacuum along the PVD was adopted as illustrated in Figure 1-(c). This was mainly due to convenience. Later, with experimental evidence, linear decay of vacuum loss was adopted as a reasonable approximation (Figure 1-b). However, in CPVDs, the geosynthetic cap is buried by the sealing layer and vacuum starts from few meters below the ground surface (Figure 1-d). This makes the vacuum distribution to be somewhat complex in shape. Also, partially penetrated PVDs in the case of a high permeable layer at the bottom of the clay deposit can have vacuum distributions with depth such as that illustrated in Figure 1-(a).

This paper presents a numerical method to model vacuum suction along the depth of PVD in a very convenient and versatile manner and it is illustrated through unit cell analysis (Fig. 1-e). The effect of the vacuum loss and shape of vacuum distribution with depth is also discussed.

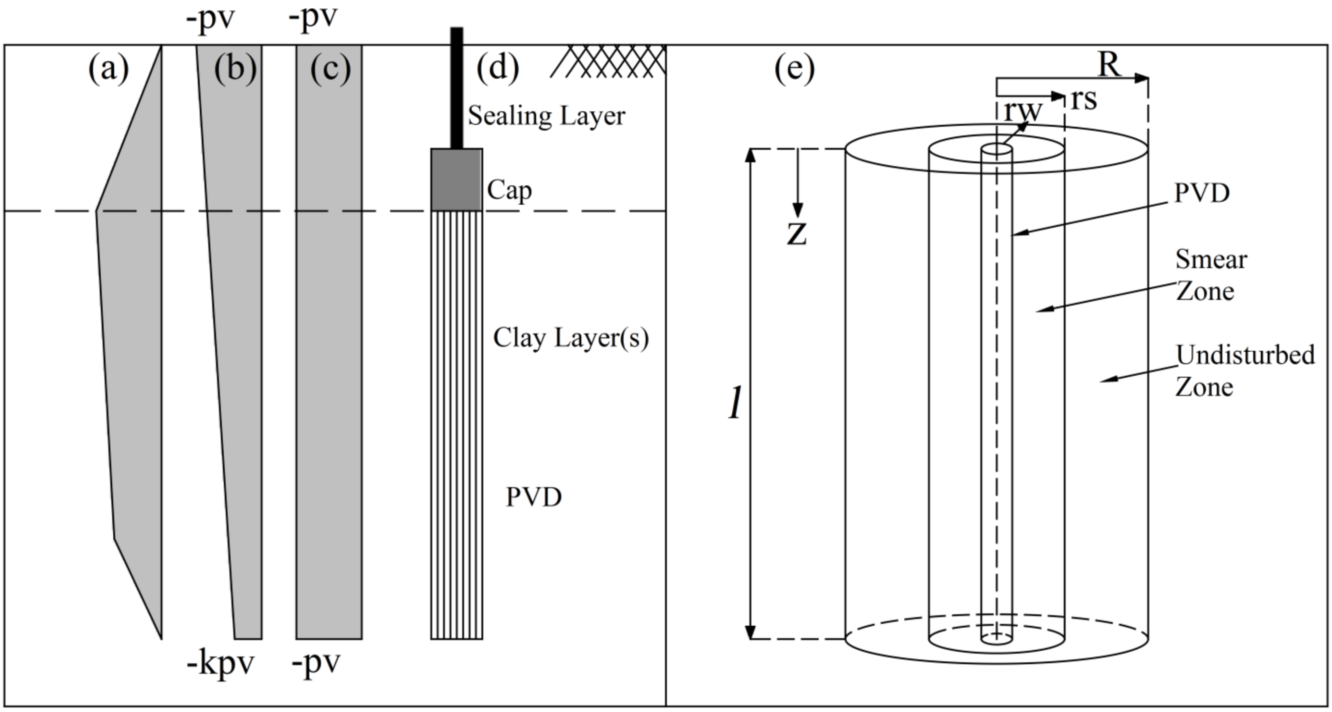

Figure 1: Vacuum distributions with depth (a, b, c); PVD with Cap (d); Unit cell (e)

2 METHODOLOGY

Vacuum suction within a unit cell (Figure 1-e) can be generally written as a function of depth (z) and radial distance (r) as,

$$p_{vac} = p_{v-max} f(z,r) \tag{1}$$

where p_{vac} = vacuum suction at a given point, $p_{v\text{-}max}$ = maximum vacuum value. The function $f(z,r)$ defines the shape of the vacuum distribution such that multiplication by the maximum vacuum applied gives the true distribution. For a liner decay of vacuum loss at a constant rate of k_1 kPa per meter of depth, Eq. (1) can be specified as Eq.(2), which is analogous to Indraratna et al. (2005) proposed method of linear decay in vacuum.

$$p_{vac} = p_{v-max}\left[1-\left(1-k_1\right)\frac{z}{l}\right] \tag{2}$$

Where l=length of the PVD. In FE implementation, the calculated negative values of vacuum suction can be fixed at the boundary of the PVD (i.e. soil PVD interface) as a negative excess pore pressure. As validated by Kumarage & Gnanendran (2017), this can give accurate predictions of the behaviour of clay for both short and long durations. However, in the case of a full embankment finite element analysis (FEA), several number of nodes needs to be defined and the vacuum suction with time changed as per the field data. In that case the above method can be a labour intensive approach. A more convenient method is to define the shape of the vacuum distribution as in Eq.(1) and make a link for the respective degree of freedom (d.o.f.) of the nodes that represent the PVD to give the required vacuum distribution. So each node need not to be defined explicitly to switch on and off vacuum or to change the intensity of vacuum over time.

The method could be used either as linear nodal constrain or non-linear nodal constrain. For example, a linear nodal constrain can be expressed as follows,

$$u_i \times m + b = u_j \tag{3}$$

where u_i = first nodal variable to link, u_j = d.o.f. of the second node to link, m and b are constants.

2.1 *Solution algorithm*

There are few different methods to obtain the solution to these types of FE formulations, each with its own merits as described by Houlsby et al. (2000). Currently the UNSW Canberra modified version of AFENA (Carter & Balaam 1995) code, the stiffness matrix is re-assembled with the modified nodal constrains. This method is relatively simple to implement and it is the technique that was used for the FEA results reported in this paper.

2.2 *Soil models*

In the first validation, Biot type (Biot 1941) fully coupled Modified Cam Clay (Roscoe & Schofield 1963) model was used. In the sensitivity analysis, a creep based viscoplastic model (Islam & Gnanendran 2017) was used. Modification of AFENA numerical code (Carter & Balaam 1995) was necessary to model vacuum consolidation and the details are presented elsewhere in Kumarage & Gnanendran (2017).

3 APPLICATION AND VALIDATION

Firstly, the method is validated against large-scale vacuum consolidation cell experimental results of Geng et al. (2012) performed on the clay from Moruya (300 km South to Sydney, Australia). Secondly, a sensitivity analysis is performed with a more general type of vacuum distribution. The experimental procedure and properties of clay from Moruya area used for the experiments have been reported by Indraratna et al. (2004) and Geng et al. (2012).

Two tests are validated in this paper and the details of tests are displayed in Table 1. Consolidation cell height was 850mm with an internal diameter of 450mm having a PVD installed at the centre to which vacuum was applied. Both tests were continued for 40 days. In FE modelling, the application of surcharge was done incrementally in 30 minutes and vacuum was applied instantly after the application of surcharge.

Table 1: Details of experiments

Test Number	Applied Vacuum suction (kPa)	Applied Surcharge pressure (kPa)	Preconsolidation Pressure (kPa)
SV1	20	30	20
SV2	40	30	20

3.1 *Vacuum distribution*

The vacuum distributions measured in two tests are illustrated in Figure 2. This distribution was approximated by a third order polynomial function as in Eq.(4),

$$p_{vac} = a_1 + a_2 h + a_3 h^2 + a_4 h^3 \tag{4}$$

where p_{vac}= vacuum suction at given depth, h= height of the PVD, a_i= respective constants. In FE implementation, only the top most node in the mesh was explicitly defined and other nodes in the PVD soil interface was coupled to satisfy the above polynomial function. Dimensions of the FE mesh adopted are R=225 mm, r_s=100 mm and l=850 mm to match the experimental setup (Figure 3-a).

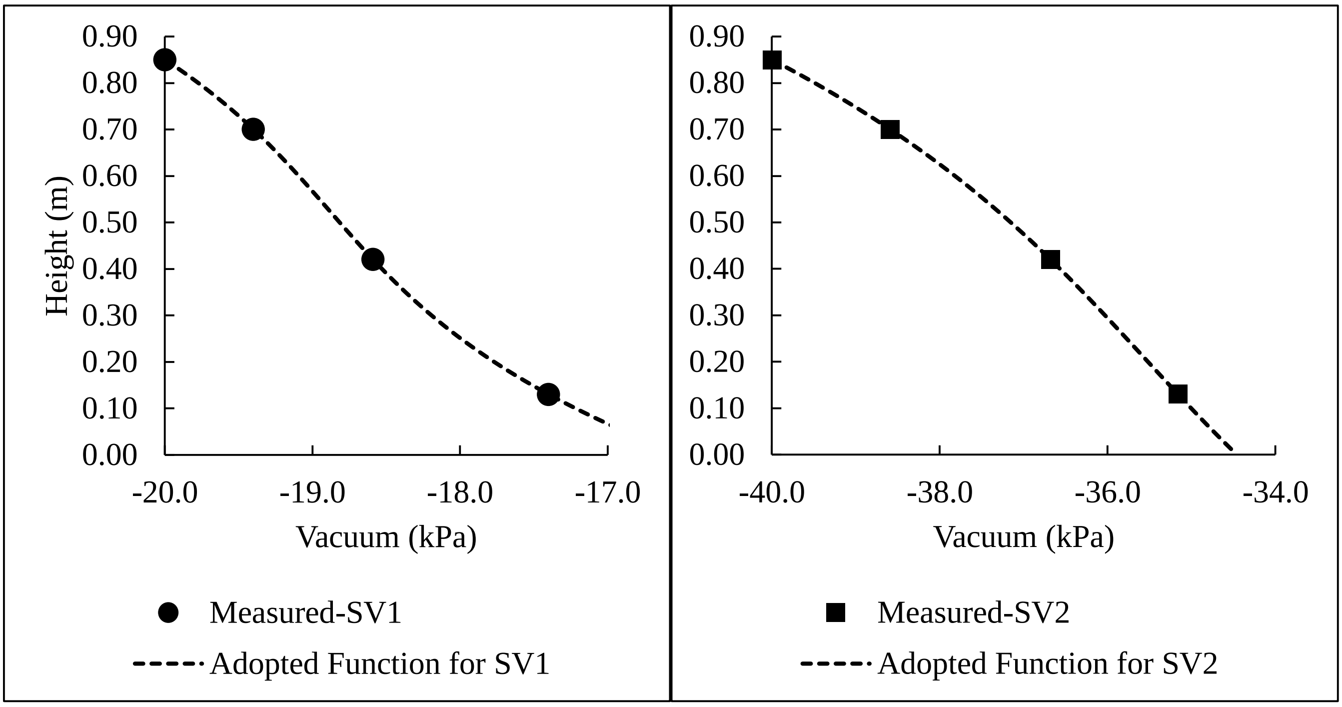

Figure 2: Vacuum distribution measured and adopted polynomial function (Experimental data adopted from Geng et al., 2012)

The results of the FE analysis and laboratory results have been compared in Figure 4. Generally, there is a good agreement between measured data and FE predictions. A maximum error of 6 kPa in excess pore pressure was observed in SV2 test around 15 days.

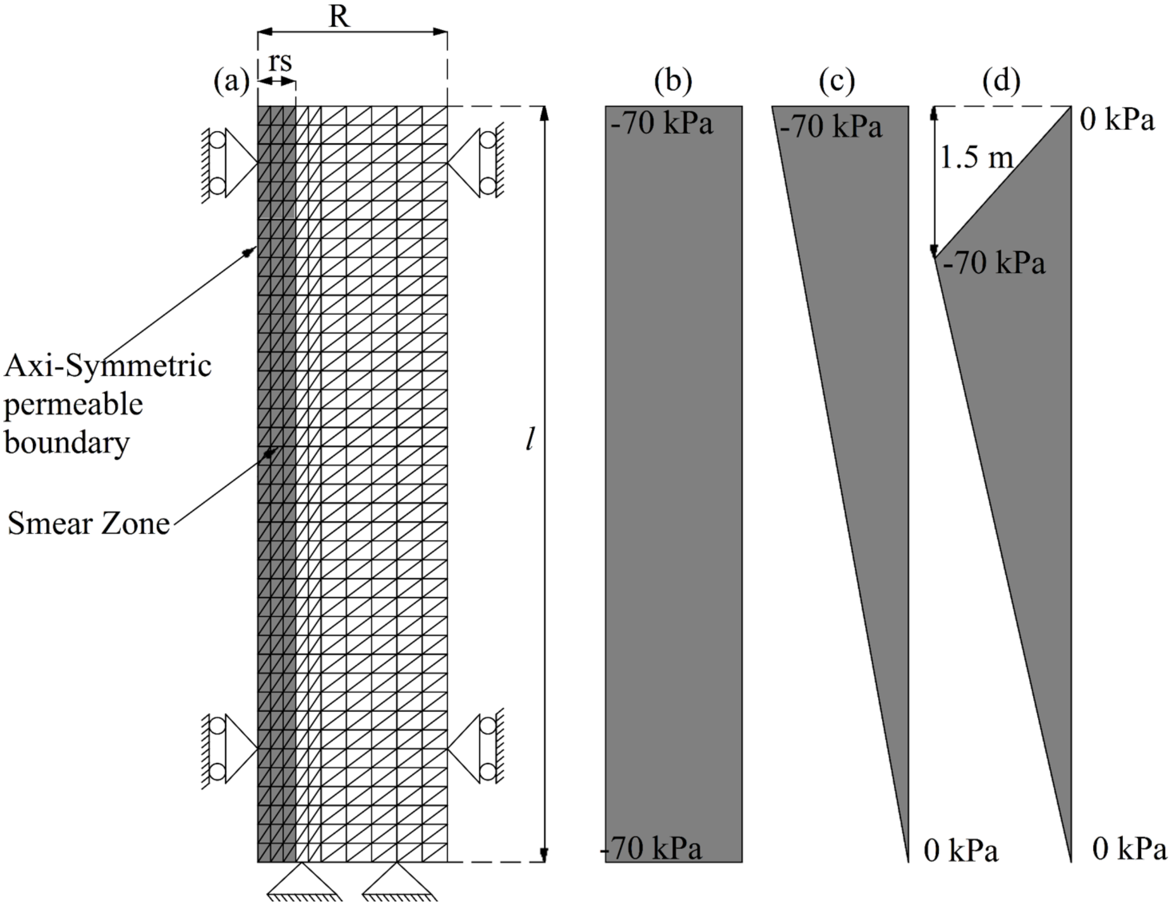

Figure 3: FE Mesh adopted for the analysis

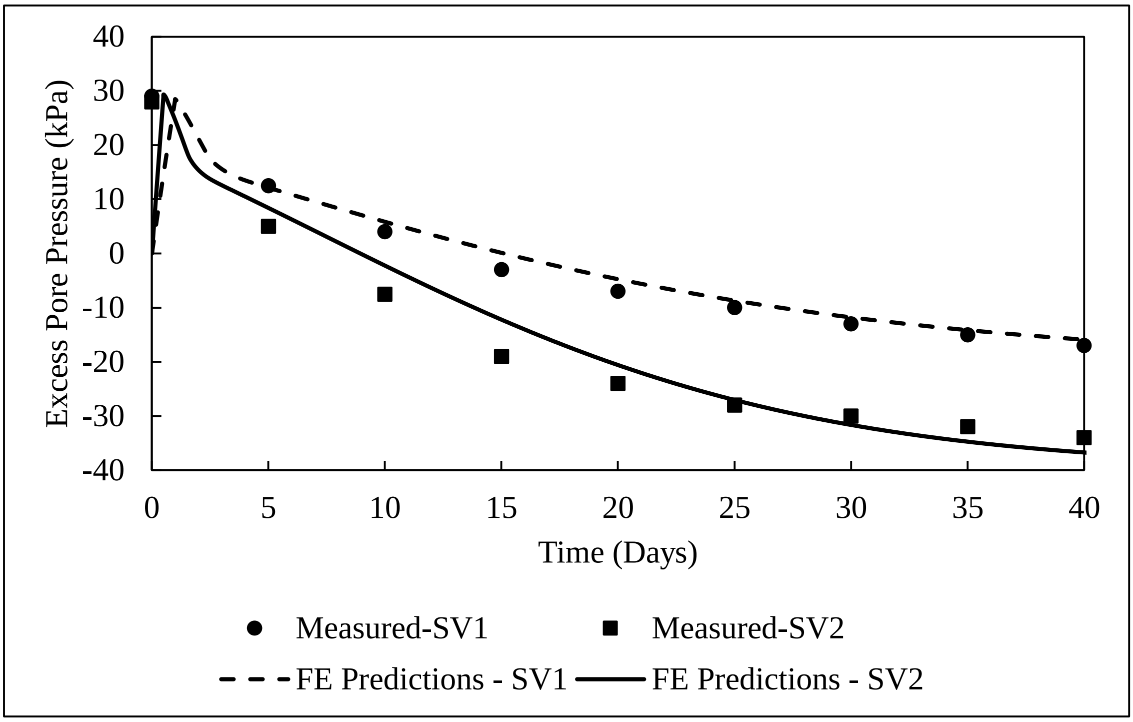

Figure 4: Measured and predicted excess pore pressures in SV1 and SV2 tests

3.2 *Sensitivity analysis*

The effect of the vacuum distribution with depth can be illustrated using a sensitivity analysis. The dimensions of the unit cell was changed to R=0.5 m and l=10 m for convenience (Figure 3-a). Soil parameters adopted are displayed in the Table 2. These parameters attribute to the soft soil in Ballina area reported by Pineda et al. (2016).

Table 2: Soil parameters adopted for the sensitivity analysis

Parameter	Value
M	1.515
λ	0.525
κ	0.053
e_0	2.80
C_α	0.057
K_h(m/s)*10	9.38
p'_c (kPa)	60

M=Slope of the Critical State Line; λ=Compression index; κ=Recompression index; e_0=Initial void ratio; C_α=Creep coefficient; k_h=Horizontal permeability; p'_c=Initial size of the yield locus.

The maximum vacuum applied was -70 kPa and the surcharge applied was 70 kPa. The distributions of applied vacuum in each case are illustrated in Figure 3 (b), (c) and (d). Apparently, vacuum distribution (b) imposes twice higher vacuum than distribution (c), which intern results in larger settlement (In this case the ultimate settlement may not be obvious since Ballina clay shows very high compression and creep). However, when comparing the distributions (c) and (d), it may not be intuitive to infer which distribution imposes higher vacuum at the soil-PVD interface. In this case, it is more appropriate to integrate the vacuum distribution over the full depth for comparison.

After 1000 days, distributions (b), (c) and (d) have resulted in overall surface strain of 20%, 17.2% and 18.2% respectively. Vacuum distributions (c) and (d) have only 1% difference in the surface strain. Whether this is significant or not depends on the total thickness of the clay deposit. Since vacuum assisted PVDs are often used for the stabilisation of thick clay deposits (>10m), this strain can be significant. When comparing the settlements for the non-vacuum case with the full vacuum (distribution-b) case, the time duration to complete 90% of the primary consolidation with vacuum takes one third of the time of conventional method. This observation agrees with the results of other researches (e.g. Lam et al. 2015; Saowapakpiboon et al. 2010). However, when long-term effects are considered, the effectiveness of vacuum consolidation is much higher. The reason for the continuous settlements after ~500 days is due to the creep based viscoplastic model used for the sensitivity analysis and the validity of the creep model has been discussed elsewhere in Kumarage & Gnanendran (2017).

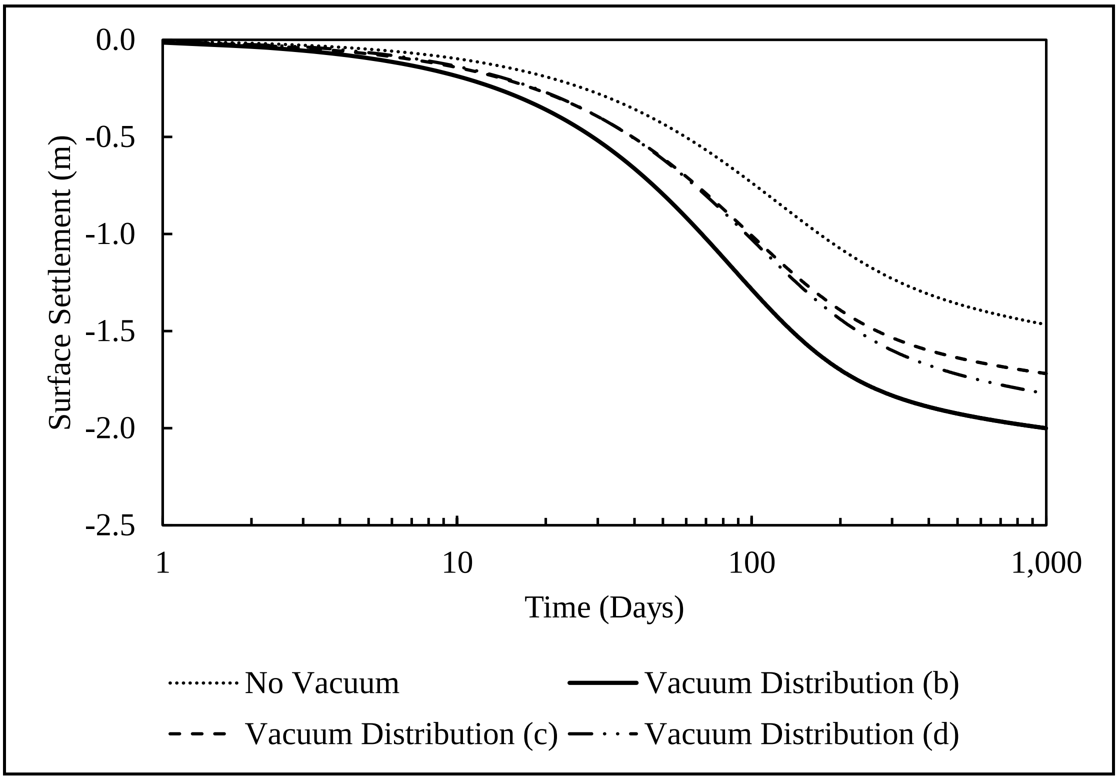

Figure 5: Surface Settlement for different vacuum distributions

4 SUMMARY AND CONCLUDING REMARKS

Patterns of vacuum suction distribution in laboratory scale has been investigated using unit cell analyses in this paper. It has been shown that vacuum suction can be practically of a complex shape than a linear reduction. Modelling such distribution in a full embankment can be challenging. The nodal constrain method has been proposed and validated against measured data. The effect of different vacuum distributions has been discussed. When surface settlements are compared, a maximum of 3% difference in overall strain was observed in this regard. In a thick clay deposit, this can be significant. However, modelling linear reduction of vacuum is still acceptable at least for preliminary investigation since the method is very easy to implement and only 1% different in strain was observed, which may not be significant for a shallow deposit or laboratory experiments.

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