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Effects of Partially Penetrating Prefabricated Vertical Drains and Loading Patterns on Vacuum Consolidation

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ABSTRACT: In this study, numerical modeling of a multi-drain system is employed to determine the optimum penetration depth of prefabricated vertical drains (PVDs) and the vacuum pressure that provides the maximum consolidation settlement and less lateral displacements. The plane strain analysis using an equivalent permeability with transformed unit cell geometry was considered for varying drain length and vacuum load. The effects of the vertical drain length and vacuum pressure on soft clay consolidation were examined through time for 90% degree of consolidation, associated settlement and lateral displacement.

1. INTRODUCTION

Much of Australian railway tracks traverse coastal areas containing soft soils and marine deposits. Pre-construction stabilization of soft formation soils by applying a surcharge load alone often takes too long. The installation of prefabricated vertical drains (PVDs) and vacuum pressure can reduce the preloading period significantly by decreasing the drainage path length, sometimes by a factor of 10 or more (Chu et al. 2004). Beneath railway tracks, the loaded area is significantly small in comparison with the thickness of the soft soil layer. The increase in vertical stress is usually sustained within the first several meters of the formation (Runnesson et al., 1985; Jamiolkowski, et al. 1983). In this context, there is no need for improving the entire depth of the soft clay deposit, hence, relatively short PVDs without any prolonged preloading may still be sufficient to support the load with acceptable track deformation. Vacuum pressure can act as an apparent surcharge load and ensure a reduction of the outward lateral displacement (Bergado et al. 2002). Due to the complexity of the problem, the consolidation due to partially penetrating drains is only analysed using a unit cell approach (Hart et al., 1958; Tang and Onitsuka, 1998). An advantage would be gained if it were possible to optimize the vertical drain configuration and vacuum pressure to minimize consolidation time and effectively control lateral displacement (Indraratna et al. 2005).

In this study, the effects of partially penetrating vertical drains and the vacuum pressure are numerically investigated through settlement and corresponding lateral displacements.

2. THEORETICAL BACKGROUND

A simplified plane strain (2-D) finite element analysis can be readily adopted to most field situations, in order to accurately predict the soil behaviour underneath a long embankment that has a compatible geometry for plane strain conditions (Indraratna and Redana, 2000; Chai et al. 2001). Indraratna et al. (2005) have shown that equivalent soil paprmeters are needed when a plane strain analysis is employed. A summary of the theoretical background for conversion from the axisymmetric to the equivalent plane strain model is presented below for the readers' benefit.

According to Figure 1, the ratio of the smear zone permeability to the undisturbed zone permeability is obtained by (Indraratna et al., 2005a):

$$\frac{k_{s,ps}}{k_{h,ps}} = \beta / \left(\frac{k_{h,ps}}{k_{h,ax}} \left[\ln\left(\frac{n}{s}\right) + \frac{k_{h,ax}}{k_{s,ax}} \ln(s) - \frac{3}{4} \right] - \alpha \right) \quad (1)$$

In the above, $\alpha = 0.67 \times (n-s)^3 / n^2 (n-1)$ and $\beta = \frac{2(s-1)}{n^2(n-1)}\left[n(n-s-1) + \frac{1}{3}(s^2+s+1) \right]$

where, $n = d_e/d_w$, s = d_s/d_w, d_e = equivalent diameter of cylinder of soil around drain, d_s = diameter of smear zone and d_w = diameter of drain well, k_h = average horizontal permeability in the undistrubed zone (m/s), and k_s = average horizontal permeability in the smear zone (m/s).

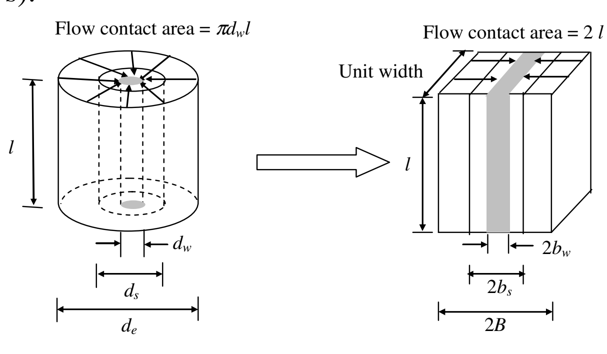


FIG. 1 Geometric conversion between (a) axisymmetric condition and (b) equivalent plane strain condition (after Indraratna et al., 2005a).

3. PROBLEM CHARACTERIZATION

A 2D finite element program (ABAQUS) was employed to simulate multi-drain analysis (Hibbitt et al., 2006). A total of 2000 elements of eight-node tri-linear displacement node with 8 pore pressure nodes (C3D8P) were used (Fig. 2). The dense mesh beneath the embankment is the zone of soil stabilized by PVDs. The equivalent plane strain model (Equation 1) was incorporated in the finite element code (ABAQUS) adopting the modified Cam-Clay theory (Roscoe and Burland, 1968). It is assumed that the clay is uniform and normally consolidated. The relevant soil parameters are: $\lambda = 0.14$, $\kappa=0.014$, $M= 1.2$, $e_0=1.1$, $k_h= 1.18\times10^{-9}$ m/s. Vertical drain spacing is 1m, and the values of k_h/k_s and d_s/d_w ratios are 3 and 4, respectively. The impermeable boundaries are located at the centerline, bottom and right side of the embankment.

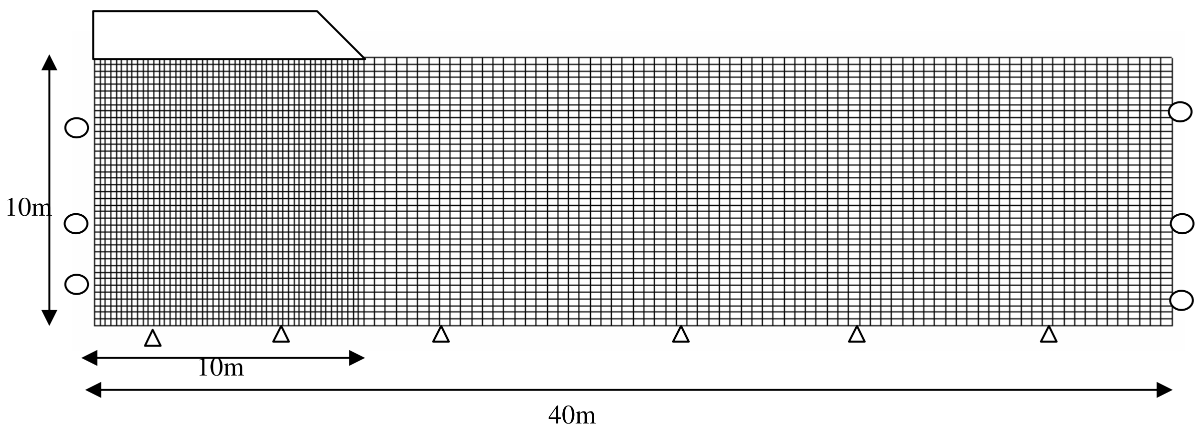


FIG. 2 Mesh discretization

4. NUMERICAL MODEL

4.1. Vertical Drains with Equal Length

Figure 3 presents vertical drain installation with varying depths of penetration. In the zone of PVD installation, the radial flow is predominant, whereas vertical flow occurs mainly below the PVD installation zone. In this section, the effect of drain length to the overall soil thickness (l_1/H) on consolidation is investigated numerically.

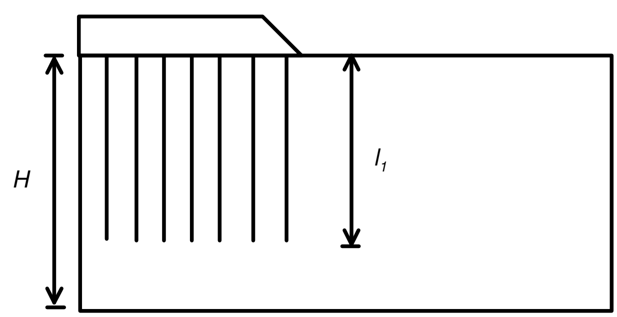
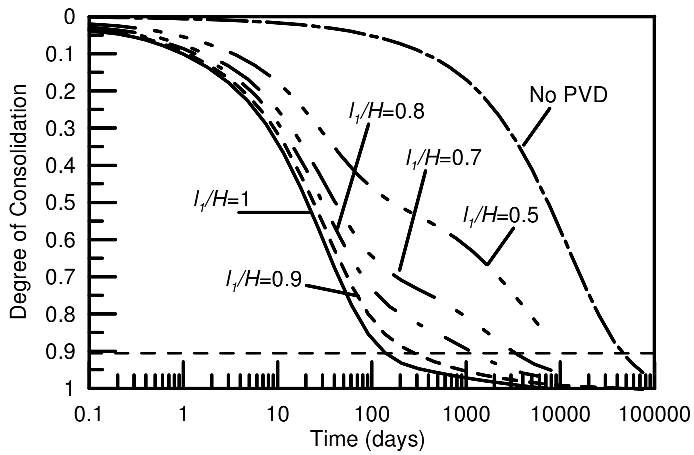


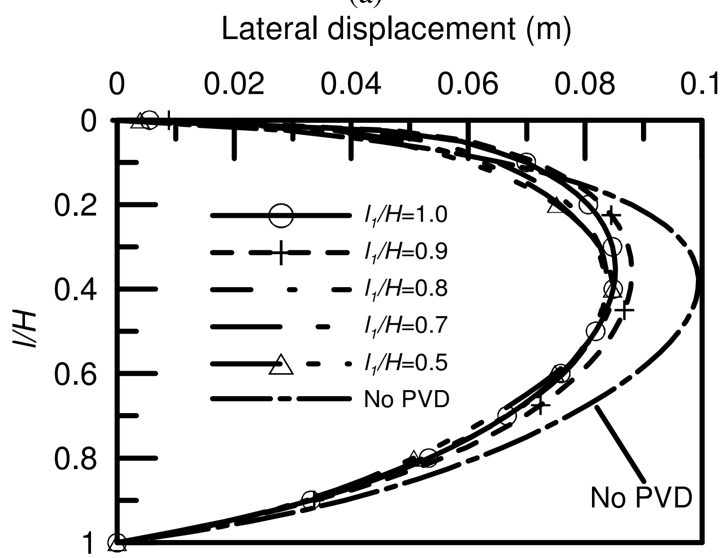
FIG. 3 Partially penetrating vertical drains of equal length

Figure 4 illustrates the effect of partially installed vertical drains (i.e. different l_1/H

ratios) on the overall degree of consolidation (Fig. 4a) and lateral displacements (Fig.4b). The degree of consolidations was calculated, based on the settlement at the centerline and the lateral displacement at the embankment toe. It can be seen that the drain length may be reduced up to 80% of the entire soft clay thickness without significantly affecting the degree of consolidation. The lateral displacements are almost the same when drain lengths are more than 50% of the clay layer thickness. The maximum lateral displacement when drains are installed can be reduced by 15%.



(a)

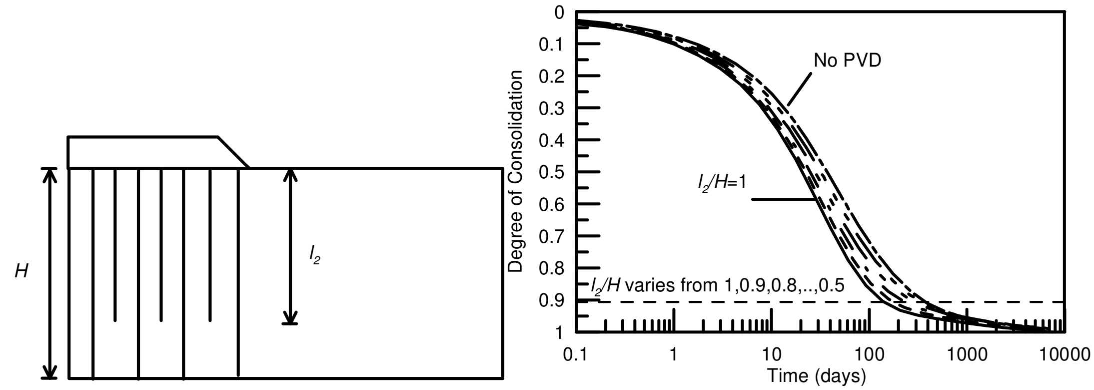


(b)

FIG. 4 Effects on partially penetrating drains (equal pattern) on (a) degrees of consolidation and (b) lateral displacement

4.2. Vertical Drains with Alternating Length

As shown in Fig. 5a, vertical drains are assumed to be installed to a depth l_2, while the drains in between these are installed to the entire depth of soft clay (H). It can be seen that l_2 can be reduced up to 0.6H without any significantly increase in the time for 90% consolidation. As expected, this installation is more effective compared to the equal length installation (Fig. 4a). The calculated lateral displacements are almost the same in all cases and only 15% less than the "no PVD" case, therefore, the results are not plotted here.

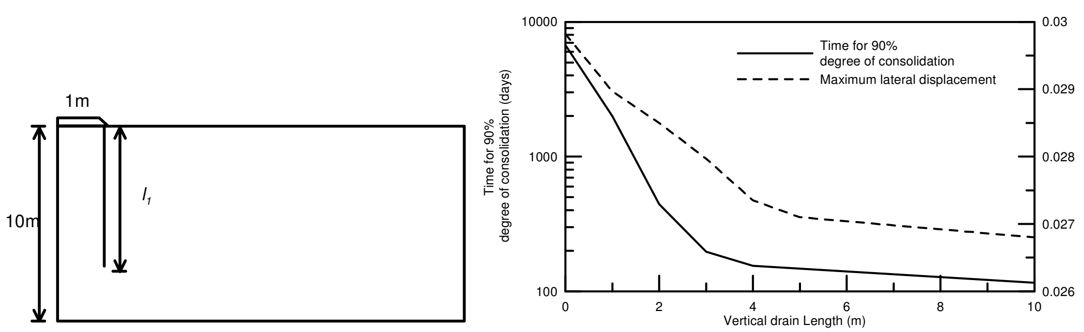


(a) (b)

FIG. 5 (a) Vertical drains with alternating length and (b) effects on the degree of consolidation

4.3. Effect of short vertical drains on narrow strip load

In this section, the vertical drain length is varied beneath narrow 2m strip load (e.g. railway tracks) to determine the required time for 90% degree of consolidation and associated lateral displacement. Vertical drains were installed at 1m spacing (Fig. 6a). The numerical analysis shows that the applied load propagates upto a depth of about 4m.



(a) (b)

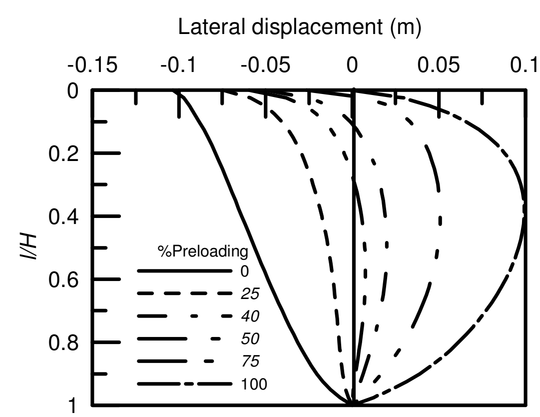
FIG. 6 (a) Vertical drains beneath narrow embankment (b) Required time for 90% degree of consolidation and associated maximum lateral movement

In terms of required time, the vertical drains installed to a depth exceeding 4m have insignificant effect on the consolidation time, however, at least 5m long vertical drains are required to reduce the generation of lateral movement. It can be concluded that the effects of vertical drains are marginal when drains are installed beyond the influence zone of the applied load, as shown in Fig. 6b (4-5m).

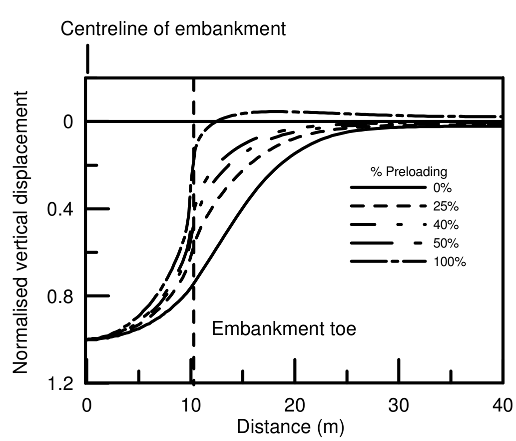
4.4. Vacuum pressure ratio

Rujikiatkamjorn et al. (2007) has discussed the benefits of vacuum pressure combined surcharge load in terms of counterbalancing the excessive lateral displacements. The outward lateral compressive strain due to surcharge can be reduced by suction (vacuum prealoding). However, this inward lateral movement may sometimes generate tension cracks in the adjacent areas. The variation of vacuum and preloading pressure to obtain a given required settlement will be considered in the numerical model to optimise the lateral displacement at the embankment toe, while identifying any zones of tension.

The variation of lateral displacement at the embankment toe due to different preloading pressures is illustrated in Fig. 7a. The negative lateral displacement represents an inward soil movement towards the centerline of the embankment. As expected, the vacuum application alone can create the maximum inward lateral movement, whereas preloading without any vacuum pressure may contribute to the maximum outward lateral movement. For a uniform soil layer, the combination of 40% surcharge preloading stress with 60% vacuum pressure seems to maintain the lateral displacements close to zero axis. Fig. 7b shows the variation of surface settlement profiles with increasing % surcharge loading. The effect of vacuum pressure alone may create settlements up to 10m away from the embankment toe. Also, due to the outward lateral displacement, soil heave can be observed beyond the toe.



(a)



(b)

FIG. 7 (a) Lateral displacements and (b) Surface settlement profiles

4.5. Effects of Vacuum Preloading on Consolidation Time

Since soft clays have low undrained shear strengths, most surcharge embankments cannot be raised beyond 2-3m without causing failure. The minimum required height to eliminate primary settlement and compensate for secondary consolidation is at least 3-4m (Hansbo, 1981). To overcome these problems, special precautions such as multi-staged construction and/or vacuum-preloading combined with PVDs, may be considered in design. In this section, the consolidation time due to multi-staged construction and vacuum-surcharge preloading is examined. It is assumed that the required preloading stress is σ_t. For a multi-staged loading, there are 2 stages of applied stress denoted by σ_1 and σ_2. The construction of the 2nd stage is assumed after 50% degree of consolidation is achieved during the 1st stage. For combined vacuum-surcharge preloading, both vacuum and surcharge pressures are applied together in a single stage. The time required for 90% consolidation can be determined by (Hansbo, 1981):

$$t_{v+p} = -\mu d_e^2 \ln(0.1)/8/c_h \quad \text{for vacuum and surcharge preloading} \qquad (2)$$

$$t_{multi} = -\mu d_e^2 \ln(0.5)/8/c_h - \mu d_e^2 \ln\left(\frac{0.1}{8(0.5\sigma_1/\sigma_t + \sigma_2/\sigma_t)c_h}\right) \quad \text{for multi-stage} \qquad (3)$$

Table 1 shows that with a single stage loading of combined vacuum and surcharge consolidation time can be reduced up to 25%. It is clear that vacuum preloading can be used effectively in a very soft clay, where a relatively high surcharge embankment cannot be raised because of potential undrained failure.

Table 1. Time reduction due to vacuum and surcharge preloading

σ_1/σ_t	σ_2/σ_t	t_{multi}/t_{v+p}
0.25	0.75	1.24
0.50	0.50	1.17
0.75	0.25	1.09

5. CONCLUSIONS

The current study of consolidation of a uniform soil with partially penetrating vertical drains and vacuum preloading has led to the following conclusions.

(a) For vertical drains with equal length beneath large embankment, the length of the drains can be shortened up to 60% soil thickness without seriously affecting the time for a given degree of consolidation. In contrast, the length of the drains with alternating length can be reduced up to 40% of the entire soil thickness.

(b) For a narrow embankment, installation of vertical drains deeper than the loading propagation zone has insignificant effect on consolidation time and lateral displacement reduction.

(c) The combination of vacuum and surcharge preloading can be used to avoid any excessive lateral displacements. Based on this simulation, almost zero lateral displacement can be obtained when using 40% preloading and 60% vacuum pressure.

(d) The application of vacuum pressure can substantially decrease the required height of the embankment and, therefore, the need for staged construction may be eliminated. Moreover, the height of temporary surcharge embankment can be reduced.

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