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Ground Improvement Optimization with Prefabricated Vertical Drains (PVD) and Surcharge Preloading

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ABSTRACT

Surcharge preloading is employed for ground improvement when the required degree of consolidation cannot be achieved by PVD alone under limited construction time and schedule. Using the constraints of minimum consolidation time, minimum degree of consolidation, and minimum ground improvement cost, an optimization method is presented in this study by Monte Carlo sampling and parameter evaluation of the PVD spacing (s) and preloading height (h). The primary consolidation settlement is formulated as a function of the preloading height according to Terzaghi theory, and the degree of consolidation is formulated as a function of the PVD spacing according to Barron's simplified theory. Under these parameters and constraints, the minimum cost of ground improvement (G) is then formulated as a function of the optimum PVD spacing and preloading height.

1. INTRODUCTION

Constructions on highly compressible soil layers are confronted with typical geotechnical issues of low bearing capacity, large settlement, and longer consolidation time. Designing foundations of structures on these areas sometimes involves soil improvement techniques as useful alternative that would limit settlements within criteria and at the same time allow for reasonable duration of construction to be completed within schedule. Prefabricated vertical drains (PVD) have been generally used to decrease the overall time required for completion of primary consolidation by shortening the drainage path length. PVD has largely replaced other drainage techniques due to its advantages of economic competitiveness, less disturbance of the soil mass, speed and simplicity of installation (Rixner et al. 1986). PVD is often used in conjunction with surcharge preloading to eliminate all or portion of the anticipated post-construction settlements caused by primary consolidation due to fill and foundation load. In general, the total cost of ground improvement with PVD and preloading should be minimized in order to obtain an optimal design. The minimum total costs represent the optimum combination of preloading and vertical drainage. Using the constraints of minimum

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consolidation time, minimum degree of consolidation, and minimum ground improvement cost, an optimization method is presented in this study by parameter evaluation of the PVD spacing and preloading height.

2. REVIEW OF RELATED LITERATURE

One dimensional consolidation settlement (S_c) according the classical theory is given by (Terzaghi 1943):

$$S_c = \frac{C_c}{1+e_0} H log\left(\frac{P_0' + \Delta p}{P_0'}\right) \quad \text{Eq. (1)}$$

where, C_c = compression index, e_o = initial void ratio; H = thickness of layer; Δp = increase in total vertical stress at the center of layer; P_o' = initial effective vertical stress at the center of layer.

Under ideal conditions, where smear effects and well resistance is neglected, the average degree of consolidation with radial drainage using PVD is given by Barron's (1948) simplified theory as follows,

$$U_h = 1 - exp\left(\frac{-8T_h}{\mu}\right) \quad \text{Eq. (2)}$$

where, $T_h=(C_h)t/D_e^2$ = time factor, $C_h=(k_h/k_v)C_v$, coefficient of consolidation for horizontal drainage, (k_h/k_v)=ratio of horizontal to vertical permeability, t=consolidation time, D_e = diameter of equivalent soil cylinder (Fig. 1), and

$$\mu = \frac{n^2}{n^2-1} ln(n) - \frac{3n^2-1}{4n^2} \quad \text{Eq. (3)}$$

where $n=D_e/d_w$=spacing ratio, d_w=equivalent diameter of the drain.

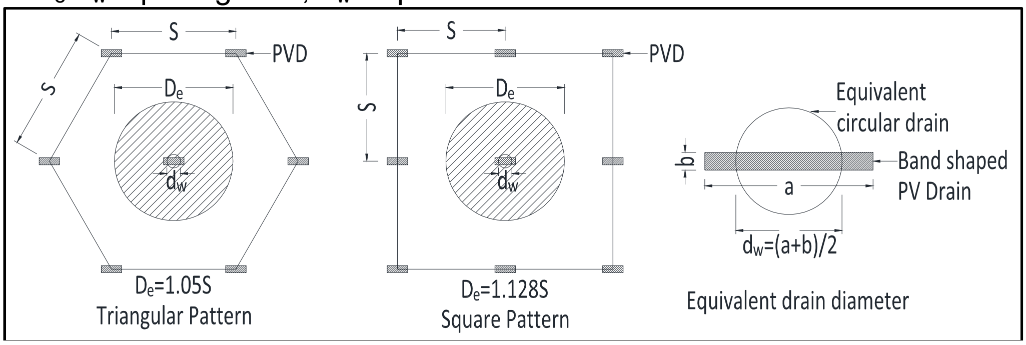

Fig. 1. Equivalent diameter of soil (D_e) and PVD (d_w) (Rixner et al. 1986).

With PVD and preloading method, the total cost of ground improvement (G) can be approximated by,

$$G = \frac{A}{s^2} LC_D + AhC_p \quad \text{Eq. (4)}$$

where A=improvement area, L=average PVD length, s=PVD spacing, h=height of preloading, C_D = unit cost of PVD (\$/m), and C_P = unit cost of preloading (\$/m^3), in which the unit cost of PVD and preloading is the sum of all the direct and indirect costs such as costs of materials, equipment, and labor. Considering all other terms are constant, an evaluation of Eq. (4) shows that the total cost of ground improvement (G) is inversely proportional to the square of the PVD spacing (s) and directly proportional to the preloading height (h). For a range of minimum and maximum PVD spacing (s_{min} and s_{max}), and a range of preloading height from zero (no preloading) to h_{max} to prevent stability problems, an optimization method is presented by Monte Carlo sampling and parameter evaluation of the PVD spacing and preloading height considering the criteria of minimum consolidation time (t_{min}), and minimum degree of consolidation U_{min} (assuming $U \approx U_h$), as shown in Fig. 2.

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Sc1 = Umin Sc;                                % target consolidation settlement
h = 0;                                        % initial preloading height
for s = smin:Δs:smax;                         % Δs = increment of PVD spacing
    Uh = 1 - exp{-8Th/μ};                     % degree of consolidation (Eq. 2)
    Sc2 = Uh Sc;                              % consolidation settlement with PVD only
    while Sc2<Sc1
        h= h + Δh;                            % Δh = increment of preloading height
        Δp' = h*γs;                           % γs = unit weight of preloading soil
        Sc' = Cc/(1+e0) H log((P'0+Δp+Δp')/P'0) ;  % consolidation settlement with preload
        Sc2 = Uh Sc' ;                        % settlement with PVD and preload
    end;
    G = (A/s^2) L CD + A h Cp;                % total cost of ground improvement (Eq. 4)
end;
plot(s,G); plot(h,G);                         % graph of G versus s and h
plot(s,h);                                    % graph of optimum combination of s and h
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Fig. 2. Matlab pseudo code for PVD/Preload ground improvement optimization scheme

From the graph of G versus s and h, the minimum total cost of ground improvement is determined, in which at d(G)=0 represents the optimum combination of PVD spacing and preloading height.

3. APPLICATION EXAMPLE

A reclamation work for a development project was reported by Chen (2004) on a coastal area at Pulau Indah, Klang, Malaysia on a site approximately 200m wide and 650m long, in which the average ground level within the area was about +5m. The development required to have a designed surface level of +7.2m, in which an average of 2.2m fill was required. The subsoil at site mainly consists of very soft and highly compressible silty clay with range of properties shown in Table 1. It was decided to improve the soil with PVD and preload so that the anticipated long term and large settlement can be eliminated or significantly reduced. For this project the targeted resting period for minimum degree of consolidation U_{min}=90% with preloading was 4 months (t_{min}). A band shaped PV drain with an equivalent diameter (d_w) of 50mm was used. For the purpose of this investigative study with conservative cost estimates, averaged thickness (H) and lower bound C_v soil properties, and a unit cost of 2.5\$/m for PVD and 10.0\$/m^3 for preloading were used. Using the ground improvement optimization method shown in Fig. 2, Figs. 3(a-b) shows the total ground improvement costs at optimized combinations of PVD spacing (s) and preloading height (h) (Fig. 3c) that would meet the minimum criteria for degree of consolidation and minimum preloading time. Due to the natural variability of the subsoil properties as well as the limitations of analytical theory, the geotechnical consultant adopted a final design of 1.0m PVD spacing with surcharge level to elevation +10m or about 2.8m preload height.

Field settlement monitoring results showed about 93% degree of consolidation achieved in about 4months. It can be seen from Fig. 3 that the soil consolidation parameters (k_h/k_v, C_v, C_h, CR) significantly affects the determination of the optimum combination of PVD spacing and preloading height and the minimum ground improvement cost, and therefore should be properly evaluated in design.

Table 1. Soil profile properties

Thickness of compressible layer, H (m)	10 - 25
Compression ratio, $CR=C_c/(1+e_0)$	0.15 – 0.30
Vertical coefficient of consolidation, C_v (m^2/year)	1 - 3
Ave. eff. unit weight of compressible soil layer, γ' (kN/m^3)	10
Ave. unit weight of preloading soil, γ_s (kN/m^3)	18
Ave. effective permanent load due to total thickness of fill accounting for settlements, Δp (kPa)	52.4

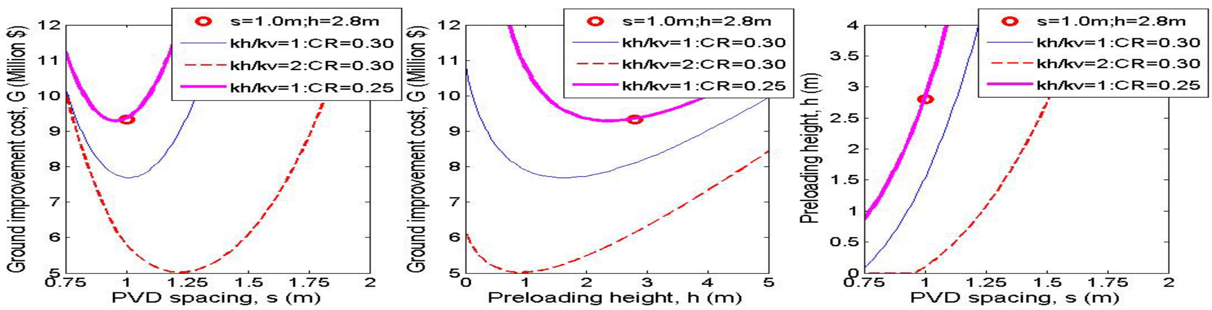

Fig. 3. Ground improvement cost at optimized PVD spacing and preloading.

4. CONCLUSIONS

This study presents an optimization scheme by Monte Carlo sampling and parameter evaluation that would provide design guidelines in the selection of the optimum PVD spacing and preloading height at minimum ground improvement cost. Results have shown that the optimized ground improvement parameters are significantly affected by the variation of the soil consolidation properties. Among the various combinations of PVD spacing and preloading height meeting the required minimum criteria for degree of consolidation and minimum consolidation time, the optimized design is selected in which the total ground improvement cost is a minimum.

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