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Analytical Studies on The Use of Stiffer Drains For Soft Soil Improvement

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Abstract. The objective of the present study is to examine the use of stiffer drains for accelerating consolidation and soft soil improvement. Higher drained elastic modulus of stiff drains when compared to soft clay is assumed in the study. Soft soil and stiffer drains are considered to deform one dimensionally during the consolidation process. The analytical solutions presented in the study are based on the vertical and radial consolidation after Terzaghi 1D and Barron solutions for free draining wells respectively. The study was carried out in the framework of a unit cell. Equal strain between the stiffer drain and the surrounding soil at any depth is assumed in the solution. The solution also accounts for the changes in stress on stiffer drain and the soft soil which is also presented in terms of stress concentration ratio, and improvement in the dissipation of excess pore water pressure with the installation of stiffer drains is illustrated. The study demonstrates dissipation of excess pore water pressure by two factors, drainage and reduction of vertical stress on soft soil during consolidation. However, influence of any lateral deformation of the drain is not considered. Modified coefficients of consolidation which account for the effects of modular ratio are adopted. The acceleration in rate of consolidation by changing modular ratio (ratio of elastic moduli of drain to soft soil) and diameter ratio (ratio of influence diameter to drain diameter) is also presented.

Keywords: Soft soil improvement, Soft clay, Stiffer drains, Consolidation, Modular ratio

1 Introduction

Stone columns have gained widespread importance as a ground improvement technique in soft clay to increase bearing capacity and reduce settlement. Several researchers have analysed this through experimental and analytical means. Stone columns also accelerate the process of consolidation by providing an additional drainage path. This was concluded from field studies [7], analytical studies [8] and numerical solutions [6]. Load transfer from soil to stone column also caused dissipation of excess pore water pressure. Analytical studies by Han and Ye (2001) developed simplified closedform solutions to estimate the rate of consolidation by stone columns. Practically, stone columns lack sufficient lateral confinement in very soft soils (c_u < 15 kPa) which hinders the gain of stiffness. They would undergo a bulging failure thereby preventing further load transfer from the soil. So the objective of this paper is to analyse the rate of consolidation due to stiffer drains analytically. Numerical solution by Balaam and Booker (1981) also showed that increase in modular ratio also increases the rate of consolidation. The objective of this study is to estimate the increased rate of consolidation in stiffer drains i.e. drains with increased modular ratio. Han and Ye (2001) also analysed the dissipation of pore water pressure as a result of drainage and vertical stress reduction. This study also aims at analysing the contribution of drainage and vertical stress reduction in pore water pressure dissipation due to stiffer drains. Equal strain rate of consolidation is adopted in this study. Effect of smear and clogging is not considered.

2 Review of Analytical Solutions

Barron (1947) solution considered consolidation of fine grained soils by drained wells. The modular ratio (ratio of elastic moduli of drain to soft soil) typically varies from 10 to 20 as given by Barksdale and Bachus (1983). This difference in stiffness was ignored in Barron's solution. Assumptions made by Barron are: (i) Water is incompressible in saturated soil and initially all the loads are taken by excess pore water pressure (ii) Only vertical deformation of soil is allowed (iii) A circular influence zone of drain well is considered (iv) Uniform distribution of load over the compressible soil zone. Barron's theory yields a partial differential equation for axisymmetric flow considering that reduction in soil volume and discharge of water from soil are equal.

$$c_r\left(\frac{1}{r}\frac{\partial u}{\partial r}+\frac{\partial^2 u}{\partial r^2}\right)+c_v\frac{\partial^2 u}{\partial z^2}=\frac{\partial \bar{u}}{\partial t} \quad (1)$$

where c_r = coefficient of radial consolidation, c_v = coefficient of vertical consolidation, u = excess pore water pressure anywhere in the soil, $\bar{u}$ = average excess pore water pressure.

The flow in (1) is decomposed into vertical and radial flows.

$$\frac{\partial u_z}{\partial t}=c_v\frac{\partial^2 u_z}{\partial z^2} \quad (2)$$

$$\frac{\partial u_r}{\partial t}=c_r\left(\frac{1}{r}\frac{\partial u_r}{\partial r}+\frac{\partial^2 u_r}{\partial r^2}\right) \quad (3)$$

where u_z and u_r are excess pore water pressures due to vertical flow alone and radial flow alone respectively.

Solution of (2) is the solution is the solution of Terzaghi 1-D consolidation. Solution of (3) can be written as

$$u_r=\frac{4\bar{u}}{d_e^2\,F(N)}\left[r_e^2\ \ln\left(\frac{r}{r_c}\right)-\frac{r^2-r_c^2}{2}\right] \quad (4)$$

where $\bar{u} = u_0 e^{\lambda}$, $\lambda = -\frac{8T_r}{F(N)}, u_0$ = excess pore water pressure initially, $F(N) = \left[\frac{N^2}{N^2-1}\right]\ln(N) - \frac{3N^2-1}{4N^2}$, N = diameter ratio (d_e / d_c), $T_r = c_r t / d_e^2$. Average degree of consolidation in radial direction is given by

$$U_r = 1 - exp^{-\left[\frac{8}{F(N)}\right]T_r} \tag{5}$$

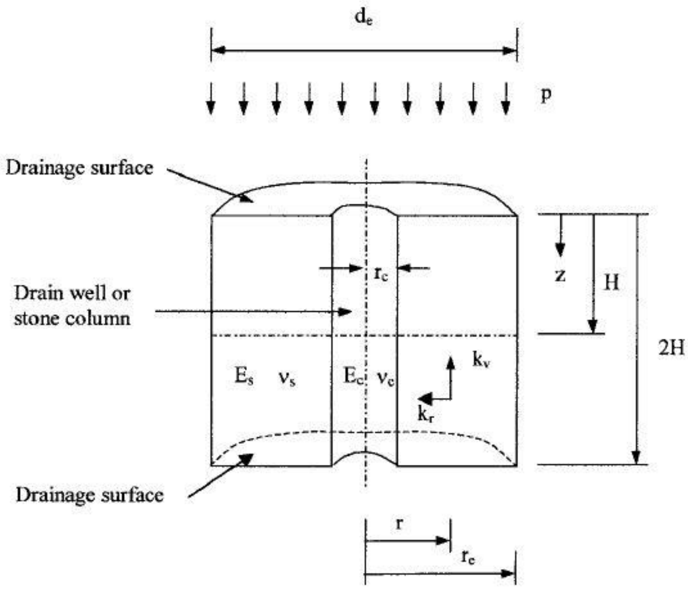

Fig. 1. Terms used in model (Adopted after Han and Ye 2001)

Han and Ye (2001) modified Barron's solution by taking stiffness of stone columns into consideration. They assumed equal strain rate of consolidation at any depth and considered effective drained modulus for modular ratio. Water was considered to be incompressible and smear and clogging effects were neglected. A modified equation for axisymmetric flow was proposed.

$$\frac{k_r}{\gamma_w}\left(\frac{1}{r}\frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial r^2}\right) + \frac{k_v}{\gamma_w}\frac{\partial^2 u}{\partial z^2} = \frac{m_{v,s}m_{v,c}(1-a_s)}{m_{v,c}(1-a_s)+m_{v,s}a_s}\frac{\partial \bar{u}}{\partial t} \tag{6}$$

where $m_{v,s}$ and $m_{v,c}$ are coefficients of volume compressibility of soil and stone column respectively, $k_r$and k_v are coefficients of radial and vertical permeability respectively, a_s is area replacement ratio i.e. ratio of area of stone column to the total influence area. Equation (6) is simplified and written as

$$c_r'\left(\frac{1}{r}\frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial r^2}\right) + c_v'\frac{\partial^2 u}{\partial z^2} = \frac{\partial \bar{u}}{\partial t} \tag{7}$$

where c_r' and c_v' are modified coefficients of consolidation in radial and vertical directions respectively and can be written as

$$c_r' = \left(\frac{k_r}{\gamma_w}\right)\frac{m_{v,c}(1-a_s)+m_{v,s}a_s}{m_{v,s}m_{v,c}(1-a_s)} \tag{8}$$

$$c_v' = \left(\frac{k_v}{\gamma_w}\right)\frac{m_{v,c}(1-a_s)+m_{v,s}a_s}{m_{v,s}m_{v,c}(1-a_s)} \tag{9}$$

For an elastic body, coefficient of compressibility can be expressed as

$$m_v = \frac{(1+\nu)(1-2\nu)}{E\,(1-\nu)} \tag{10}$$

where ν is Poisson's ratio and E is elastic modulus. Thus,

$$\frac{m_{v,s}}{m_{v,c}} = \frac{E_c}{E_s}\frac{(1+\nu_s)(1-2\nu_s)(1-\nu_c)}{(1+\nu_c)(1-2\nu_c)(1-\nu_s)} = \xi\frac{E_c}{E_s} \tag{11}$$

where E_c and E_s are drained elastic moduli of column and soil respectively, ν_c and ν_s are Poisson's ratios of column and soil respectively, ξ is Poisson ratio factor.
The steady vertical stresses after consolidation is complete, σ_{cs} and σ_{ss} in the column and soil respectively can be written as

$$n_s = \frac{\sigma_{cs}}{\sigma_{ss}} = \frac{m_{v,s}}{m_{v,c}} = \xi\frac{E_c}{E_s} \tag{12}$$

where n_s is the steady state concentration ratio. Therefore, the modified coefficients of consolidation after simplification are given by

$$c_r' = c_r\left(1 + n_s\frac{1}{N^2-1}\right) \tag{13}$$

$$c_v' = c_v\left(1 + n_s\frac{1}{N^2-1}\right) \tag{14}$$

where N is diameter ratio.
Overall rate of consolidation including vertical and radial effects given by Carillo (1942) is expressed as

$$U_{rv} = 1 - (1 - U_r)(1 - U_v) \tag{15}$$

Han and Ye (2002) further developed solutions to account for smear effect and well resistance by considering size and permeability of smeared zone which depends on the method of installation of stone columns. However, these are not considered in the present study. Castro and Sagaseta (2009) analysed the problem by accounting for radial deformation of stone column and considered both elastic and plastic deformations. As stiffer drains are considered in the present study which do not deform laterally and whose stiffness does not depend on the lateral confinement provided by the surrounded soil, radial deformations need not be considered.

3 Analysis and Discussions

The current analysis makes the following assumptions:
(i) Water is assumed to be incompressible and drained elastic modulus is considered.
(ii) Equal rate of strain approach at any depth.
(iii) Smear and clogging effects are neglected.
A modular ratio (E_c / E_s) = 30 is considered to simulate the behaviour of stiffer drains. ν_c = 0.15, ν_s = 0.45, N (Diameter ratio) = 3 are taken from Han and Ye (2001). From Equation (12) we get n_s = 8.34 for the above values. The results obtained from n_s = 8.34 are compared to that of n_s = 5 as the latter was considered by the study in Han and Ye (2001).

3.1 Stress transfer

Increase in effective stress in the surrounding soil is calculated as

$$\Delta\sigma_s' = \Delta\bar{u}\frac{1-a_s}{1+a_s(n_s-1)} = u_0 U_{rv}\frac{1-a_s}{1+a_s(n_s-1)} \qquad (16)$$

The transfer of stress from soil to columns is called stress concentration. With time, the vertical stress on the columns increases and that on soil decreases. The stress concentration ratio increases with time and reaches steady stress concentration ratio. From Fig.2, we can see that with an increase in modular ratio (or steady state stress concentration ratio), there is an increase in vertical stress on the columns and the vertical stress on the soil decreases. The increase in vertical stress on the columns is higher as compared to the decrease in vertical stress on the soil. Modified coefficients of consolidation are considered to get a modified time factor in the stress calculation and the results are presented against vertical stresses in Fig. 3.

3.2 Stress concentration ratio

The stress transfer process is shown in terms of stress concentration ratio in Figs. 4 and 5 which approach a steady state concentration ratio and the consolidation ceases. Modified time factor is calculated corresponding to the conventional time factor and used in the equations for calculating vertical stress and pore water pressure dissipation and plotted against conventional time factor for comparison.

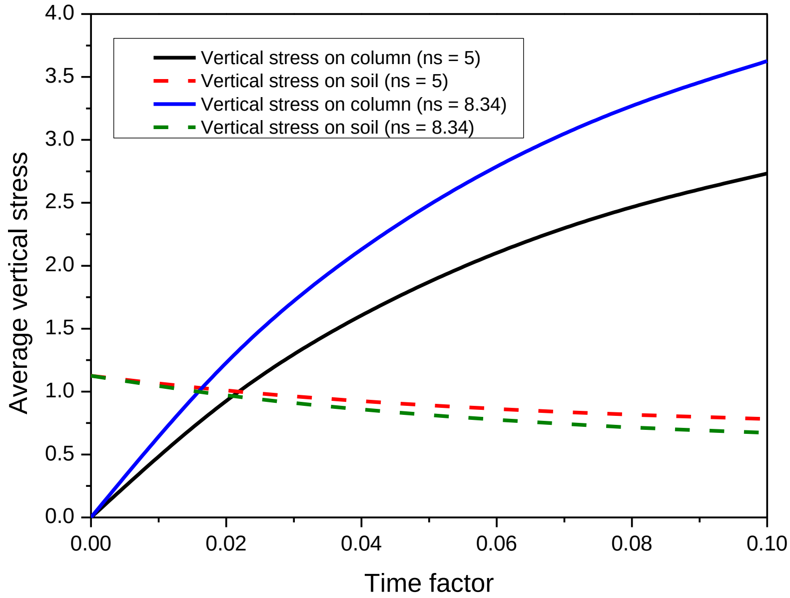

Fig. 2. Variation of average vertical stress with Time factor

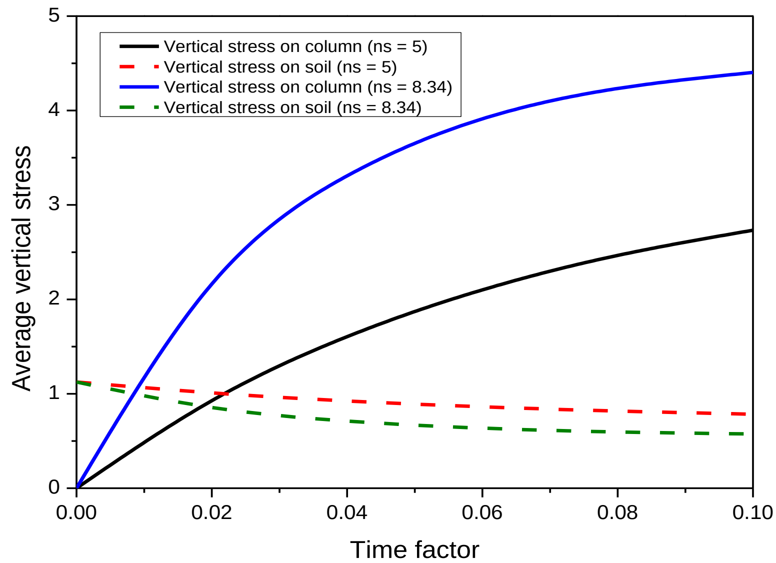

Fig. 3. Average vertical stress vs Time factor introducing modified time factor in stress calculation

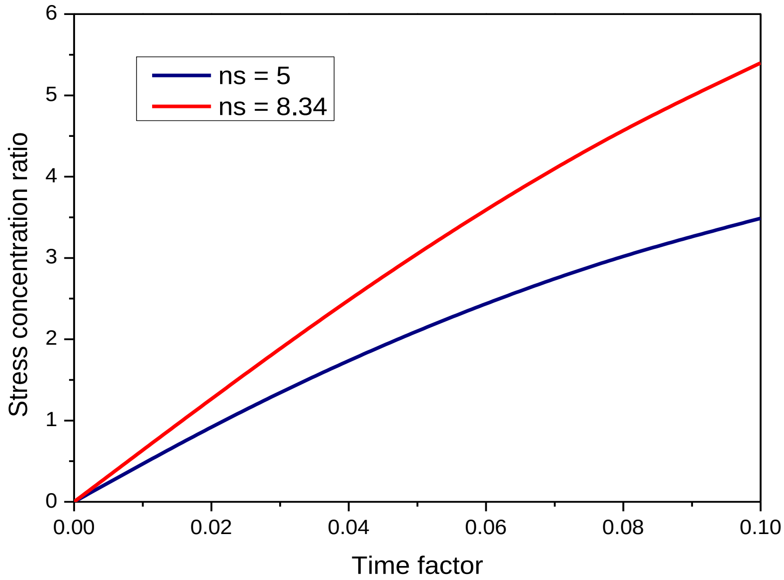

Fig. 4. Variation of stress concentration ratio vs time factor

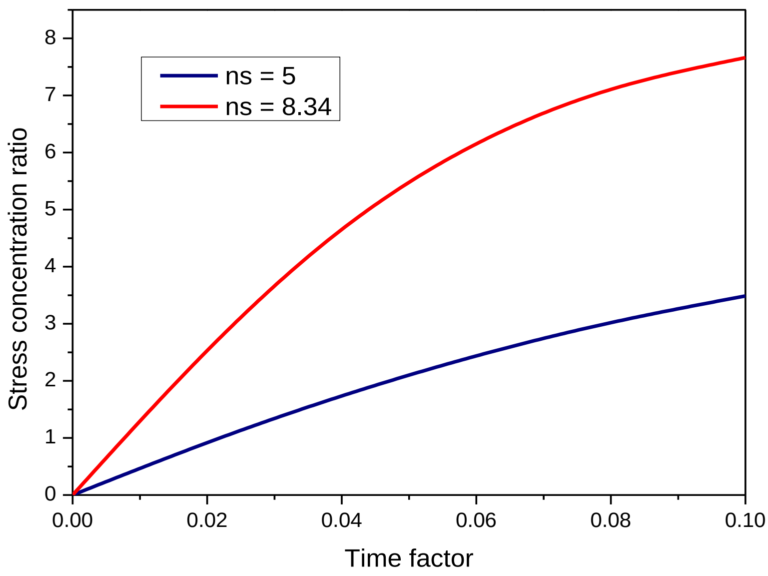

Fig. 5. Stress concentration ratio vs Time factor introducing modified time factor in stress calculation

3.3 Excess pore water pressure

Excess pore water pressure variation in the soil at any time can be written as

$$u_t = u_0 - \Delta u_{\sigma_v} - \Delta u_d \tag{17}$$

where u_t and u_0 are excess pore water pressures at t>0 and t=0 respectively, Δu_{σ_v} is reduction in excess pore water pressure due to reduction in vertical stress on the soil or due to stress transfer and Δu_d excess pore water pressure reduced due to drainage.

In Fig 6, excess pore water pressure dissipated through stress reduction is the difference between the total excess pore water pressure dissipated and the excess pore water pressure dissipated through drainage. This contribution of stress reduction towards the dissipation of pore water pressure is dependent on stress concentration ratio. Larger the stress concentration ratio, greater the dissipation. But we can see that in Fig.6, the total pore water pressure dissipated is not changed when the steady state stress concentration ratio increases but the pore pressure dissipated through stress reduction increases. This is because we have used the same degree of consolidation for both the steady state stress concentration ratios. Therefore modified coefficients of consolidation given by Han and Ye (2001) should be used to bring the effect of stiffness of drains into picture.

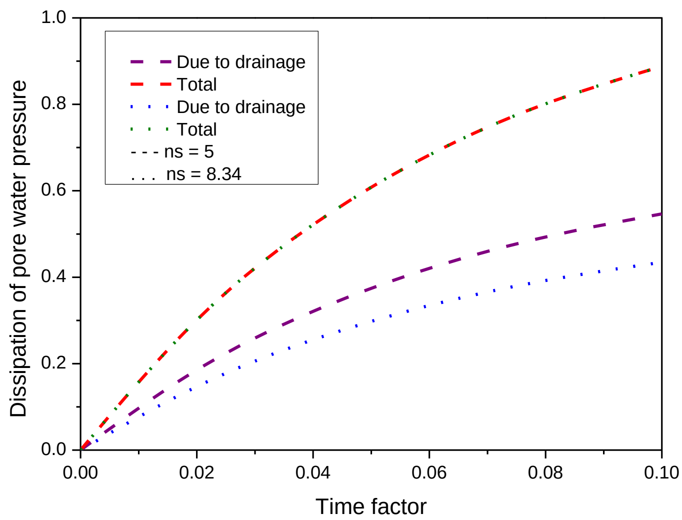

Fig. 6. Variation of dissipation of pore water pressure with time factor

From Fig. 7, we can see that though the dissipation of excess pore water pressure due to drainage accelerates in the current study in the beginning, but the final pore pressure dissipation due to drainage in the present study and by Han and Ye (2001) is identical, which attributes to the fact that the drainage conditions are same and the stiffer drains are equally permeable as that of drains assumed in the study of Han and Ye (2001). We can also observe that $\Delta u/p$ is greater than one. The presumption of all loads being carried by water in the soil at the beginning explains this. That is why stress on column in the beginning as zero.

$$\frac{\sigma_s}{p}(1-a_s)+\frac{\sigma_c}{p}a_s=1 \tag{18}$$

Substituting $\sigma_c = 0$ in the above equation and a_s (area replacement ratio) = 1/9 for N=3, we get $\sigma_s = 1.125p$. Since initially all loads are carried by water in the soil, the initial pore water pressure u_o becomes 1.125p which dissipates gradually and gives the ratio $\Delta u/p>1$ eventually.

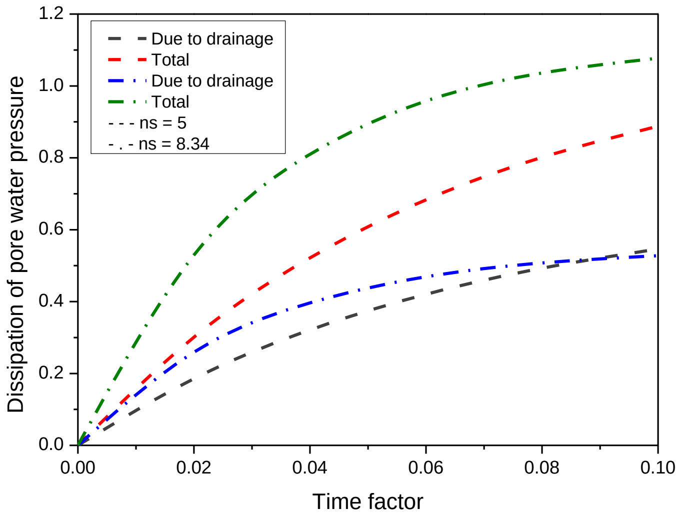

Fig. 7. Dissipation of excess pore water pressure vs Time factor introducing modified time factor in stress calculation

4 Conclusions

The rate of consolidation in the soil by using stiffer drains is studied. Stress transfer is higher if stress concentration ratio is higher, thus stiffer drains relieve more stress on the soil. The contribution of stress transfer in dissipation of excess pore water pressure increases with the increase in stress concentration ratio. These effects can be modelled accurately by using the modified coefficients of consolidation. Experimental investigations using stiffer drains need to be carried out to investigate the consolidation characteristics and economic feasibility for this to become an established field practice. Further analyses considering the smear and well resistance effects and clogging are warranted.

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