

Consolidation by vertical drains when the discharge capacity varies with depth and time

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ABSTRACT

Following the approach of Hansbo [4], a series of closed-form solutions for equal-strain consolidation were developed based on an axisymmetric unit cell in presence of a vertical drain, whose discharge capacity was varied by altering the depth, time or both simultaneously. The excess pore pressure and degree of consolidation were compared with Hansbo's results. The factors affecting the calculation results were also investigated. Some conclusions were drawn regarding the distribution of the excess pore water pressure along the ground depth and the extent of consolidation considering the varied discharge capacity.

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1. Introduction

The use of a vertical drain (e.g., a sand drain or prefabricated drain) combined with preloading offers significant benefits in improving sites with thick soil deposits by accelerating the consolidation process and has been used extensively for many decades [1]. Consolidation theory has been developed to analyse the performance of the drain–soil system based on an axisymmetric unit cell (a cylinder of soil around a single drain) in a series of research studies [2–7]. Among these studies, the solutions developed by Barron [2] and Hansbo [4] are popular and widely implemented due to their simplicity and ease of use.

Both theoretical research and field practice have indicated that the treatment and effectiveness of the vertical drain method are directly linked with the performance properties of the vertical drain, such as its discharge capacity [8,9]. The discharge capacity q_w , which is defined as a factor proportional to the in-plane hydraulic conductivity and the cross-sectional area of the drain, has been investigated by several studies in recent years [10–17]. The general conclusion has been that q_w , particularly for the slim prefabricated vertical drain (PVD), can be reduced throughout the consolidation process in the field by several factors, such as the deformation of the drain, the lateral stress and siltation. As the vertical drain is installed into thick soft ground, the lateral confinement pressure from the surrounding soil, which generally

increases with depth, causes the contraction of the drain and produces a substantial reduction in the discharge capacity [10–13]. In addition, the drain–soil interaction may cause the vertical drain to fold, crimp, bend, buckle, or kink when the soft soil subsides, and thus, the discharge capacity q_w decreases and the well resistance increases. Several investigators reported that the discharge capacity decreased considerably when the vertical consolidation strain exceeded 15% [10,14].

The aforementioned research on the discharge capacity of vertical drains indicates that q_w varies with the ground depth and elapsed time; however, limited theoretical research has focused on these effects. Chai assumed that q_w varied linearly with depth z and obtained a solution for the average excess pore pressure (EPP); however, the smear effect was ignored in the study [18]. By accounting for the effect of smear, this paper further assumes that q_w decreases exponentially with time and attempts to develop a unit cell theory assuming that the discharge capacity varies with both depth and time under an equal strain condition. The results predicted by the current solution will be compared to Hansbo's solution [4], in which q_w is kept constant, to investigate the impact of the variable discharge capacity.

2. Mathematical model

Fig. 1 presents a schematic representation of the axisymmetric unit cell, with a drainage well of radius r_w surrounded by a zone of remolded soil bounded by an outer radius r_s , which is in turn surrounded by the undisturbed soil extending to a radius of influence

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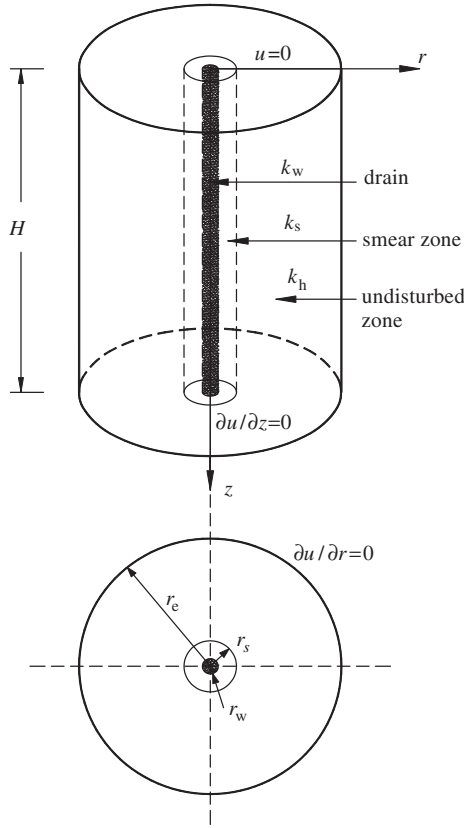


Fig. 1. The cylindrical unit cell for vertical drain ground.

r_e . The coefficients k_w , k_s and k_h are used to capture the differences in permeability of the vertical drain, smear zone and undisturbed zone, respectively. The mechanical properties of the three parts are assumed to be the same. In the analysis, the vertical drain completely penetrates the soft soil layer, and thus, the length of the drain well l is equal to the thickness of the soft layer H . A relatively stiffer stratum lies below the soft layer and is assumed to be impervious, whereas the top surface of the soft layer is completely permeable because of the presence of a layer of medium coarse sand. A widespread surcharge loading of q_0 is simulated by the instantaneous application to the upper boundary and was kept constant during the consolidation process. Additionally, r and z in Fig. 1 indicates the radial coordinates and the depth, respectively.

The basic assumptions for this paper, which were provided by Barron [2] and Hansbo [4], are stated below for completeness.

(1) Compressive strain occurs only in the vertical direction, and the radial sections of the cell remain radial during the consolidation; that is, the equal strain condition is valid. (2) Radial and vertical flow can be considered separately, and the flow in the porous medium obeys Darcy's law. (3) The quantity of water flowing through the disturbed soil zone into the drain well is equal to that flowing out from the drain. (4) The radial flow in the well can be ignored. (5) Uniform loading is imposed instantaneously and kept constant during the entire consolidation process. (6) All vertical loads are initially carried by the excess pore water pressure. (7) The top of the soft soil layer drains freely, but the bottom is completely impermeable.

In addition, the discharge capacity q_w , which is related to the coefficient of permeability of the drain k_w , is assumed to vary with depth z and time t , which can be expressed as

$$q_w = q_{w0} \left(A_1 - A_2 \frac{z}{l} \right) e^{-A_3 t} \quad \text{or} \quad k_w = k_{w0} \left(A_1 - A_2 \frac{z}{l} \right) e^{-A_3 t} \quad (1)$$

Note here that $q_w = k_w A_w$, and A_w is the cross-sectional area of the drain. In Eq. (1), q_{w0} and k_{w0} are the initial values of q_w and k_w , respectively; A_1 , A_2 and A_3 are constants with the conditions of $A_1 > 0$, $0 \leq A_2 \leq A_1$ (to ensure that q_w or k_w is non-negative) and $A_3 \geq 0$. The dimensionless constants A_1 and A_2 are used to depict the variation of the discharge capacity with depth z ; if $A_2 = 0$, the discharge capacity q_w in Eq. (1) is unchanged with depth. The dimensional coefficient A_3 (with units of $1/s$) denotes the variation of the discharge capacity with the consolidation time; a larger value of A_3 implies that q_w or k_w decreases more rapidly with time.

Based on the above assumptions, the consolidation equation for the surrounding soil (both in the smear zone and undisturbed zone) can be obtained [2,4,6]:

$$\begin{cases} -\frac{k_s}{\gamma_w} \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial u_r}{\partial r} \right) = \frac{\partial \varepsilon_v}{\partial t} & r_w \leq r \leq r_s \\ -\frac{k_h}{\gamma_w} \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial u_r}{\partial r} \right) = \frac{\partial \varepsilon_v}{\partial t} & r_s \leq r \leq r_e \end{cases} \quad (2)$$

$$\frac{\partial \varepsilon_v}{\partial t} = -m_v \frac{\partial \bar{u}_r}{\partial t} \quad (3)$$

where

$$\bar{u}_r = \frac{1}{\pi(r_e^2 - r_w^2)} \int_{r_w}^{r_e} 2\pi r u_r dr \quad (4)$$

\bar{u}_r is the average excess pore water pressure (EPP) within the soil at any depth; u_r is the EPP at any point in the soil; r is radial distance from the centre of the drain; k_h is the horizontal soil permeability; k_s is the soil permeability in the smear zone; γ_w is the unit weight of water; ε_v is the volume strain (equal to the vertical strain) of the unit cell at any depth; and m_v is the coefficient of the volume compressibility.

The consolidation equation for the continuity condition of the drain well can be derived using assumptions (3) and (4). Considering a slice of the drain well with a height of dz as illustrated in Fig. 2, the radial inflow of water from the smear zone in a unit time dt is:

$$q_r = 2\pi r_w dz dt \left. \frac{k_s}{\gamma_w} \frac{\partial u_r}{\partial r} \right|_{r=r_w} \quad (5)$$

In turn, the quantity of water that is vertically flowing through the unit can be expressed as:

$$q_z = \frac{k_w \pi r_w^2}{\gamma_w} \frac{\partial u_w}{\partial z} dt \quad (6)$$

According to assumption (3) that the drain well acts as a drainage body, the water quantity flow in and out should be equal, which yields:

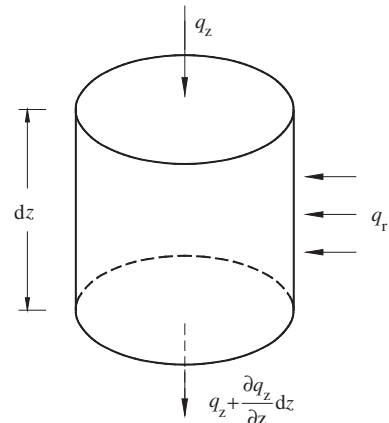


Fig. 2. Schematic diagram of flow rate continuation in the vertical drain.

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