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Consolidation analysis of clayey deposits under vacuum pressure with horizontal drains

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ABSTRACT

A method has been developed for the consolidation analysis of dredged mud or clayey soil deposits containing strip-type, prefabricated horizontal drains (PHDs), based on either the axisymmetric or plane strain unit cell theory. An approximate consolidation theory has also been proposed for a surface soil layer subjected to vacuum pressure applied through the PHDs at a shallow depth from the surface. The proposed method and the consolidation theory have then been applied to the analysis of a field project in Japan involving dredged mud consolidated by vacuum pressure with PHDs. By comparing the field-measured and analyzed results in terms of water content distributions with depth and the thickness variation of the deposit, the usefulness of the proposed method has been demonstrated.

1. Introduction

Prefabricated vertical drains (PVDs) have been extensively used to accelerate the consolidation rate of soft clayey deposits under a surcharge load with or without a vacuum pressure (Chu et al., 2006; Rowe and Taechakumthorn, 2008; Saowapakpiboon et al., 2010, 2011; Indraratna et al., 2012; Cascone and Biondi, 2013). In recent years, strip-type, prefabricated horizontal drains (PHDs) have been used in practice to accelerate the consolidation of embankments with clayey backfills (Nagahara et al., 2004; Chai and Nguyen, 2013) and the self-weight and vacuum pressure-induced consolidation of dredged mud (Shinsha et al., 2013). PHD treatment has an advantage over PVD improvement for dredged soft clayey soil with a small deposition thickness. However, there are still theoretical issues that need to be resolved for PHD-induced consolidation with or without the application of a vacuum pressure. This paper is concerned with resolving those theoretical issues.

For clayey subsoils improved by the introduction of prefabricated vertical drains (PVDs) installed on a square or triangular pattern, there are several consolidation theories available in the literature (e.g., Barron, 1948; Hansbo, 1981; Ong et al., 2012; Deng et al., 2013; Tang et al., 2013; Liu et al., 2014). However, for the case of PHDs, the vertical and horizontal spacing between the PHDs may not be equal and in many cases the region improved by a PHD is rectangular in vertical cross-section. There is no consolidation theory currently available for this particular case.

Fig. 1(a) shows a vertical cross-sectional layout of PHDs and Fig. 1(b) shows a model for numerical analysis assuming one-dimensional (1D) (vertical) deformation. For many practical cases, the treated areas are much larger than the thickness of the treated soil and the assumption of 1D deformation is realistic. The vertical spacing between adjacent PHDs is designated as S_v and the horizontal spacing as S_h (Fig. 1(a)). S_v and S_h may not be equal and usually $S_v > S_h$. Chai et al. (2011) proposed to represent the rectangular area of soil influenced by a PHD as an equivalent circular area (i.e., an axisymmetric unit cell) assuming the equal area condition (Fig. 2(b)) and to use Hansbo's (1981) solution to calculate

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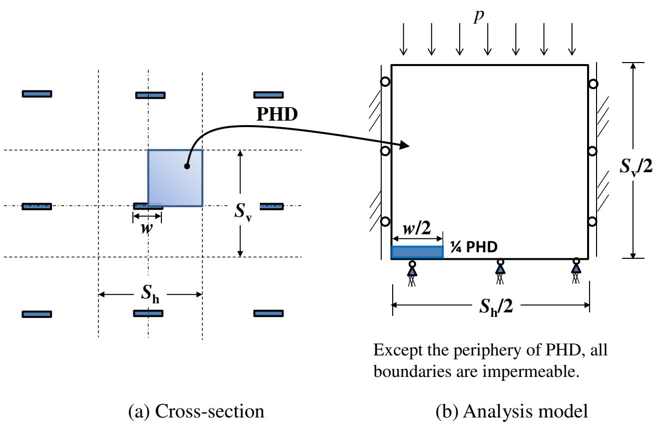

Fig. 1. Representative area of a PHD.

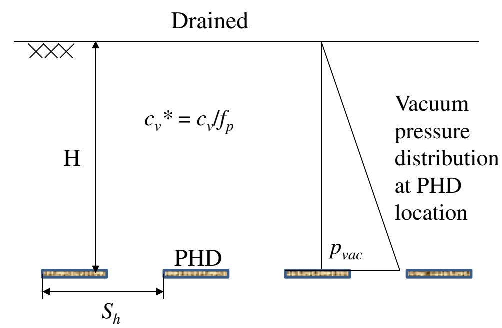

Fig. 3. A surface layer with vacuum pressure applied at a shallow depth.

the average degree of consolidation (U). Conceptually, the suitability of this assumption depends on the ratio SR = S_v/S_h, and the closer the value of this ratio is to unity, the smaller the error should be in adopting this approximation. Another factor influencing the behaviour of PHD-improved soil is the ratio between the width of an individual PHD (w) and their horizontal spacing S_h, i.e., WS = w/S_h. If the values of both SR and WS are large, the problem may be closer to a plane strain model (Fig. 2(c)) rather than an axisymmetric model (Fig. 2(b)). For most practical cases, using either the axisymmetric unit cell theory or the plane strain unit cell theory (Hird et al., 1992; Chai and Miura, 2002) will necessarily involve some error. It is therefore desirable to develop a more suitable consolidation theory for this particular problem.

As shown in Fig. 3, for a surface layer with vacuum pressure applied to the PHDs at a shallow depth, the final state in the soil will involve water flow toward the PHDs and zero vacuum pressure at the soil surface. The existing plane strain unit cell theory (Hird et al., 1992) requires an undrained boundary at the surface, which is not applicable to this situation. Furthermore, the vacuum consolidation theory for a two-way drainage boundary condition developed by Chai and Carter (2011) cannot be directly applied to this situation either, because the level of the PHDs is not a drainage boundary.

The objectives of this study are therefore: (1) developing a ‘matching’ method to modify the hydraulic conductivity (k) or the coefficient of consolidation (c) of the soil, and with the modified k or c, using Hansbo's (1981) or Hird et al.'s (1992) unit cell solutions to calculate the degree of PHD-induced consolidation; and (2) proposing an approximate consolidation theory for a surface layer under vacuum pressure applied at a shallow depth through PHDs. The matching method and the consolidation theory developed will then be applied to the analysis of a field project in Aomori, Japan, involving the consolidation of a dredged mud deposit using vacuum pressure with PHDs. A comparison of the analyzed and measured results, in terms of the distribution of water content with depth and the variation of the thickness of the deposit, is also presented, demonstrating the validity and utility of the proposed theoretical approach.

2. Proposed method

2.1. Basic equations

In Hansbo's (1981) solution for an axisymmetric unit cell, the average degree of consolidation (U) is given by:

$$U = 1 - \exp(-8T/\mu) \quad (1)$$

$$T = \frac{ct}{4r_e^2} \quad (2)$$

$$\mu = \ln(r_e/r_s) + (k/k_s)\ln(s) - \frac{3}{4} + \frac{2\pi \cdot l^2 \cdot k}{3q_w} \quad (3)$$

where c is the coefficient of consolidation of the soil, t is time, k and k_s are the hydraulic conductivities of the clayey soil and smear zone respectively, l is the drainage length of the drain, r_e is the radius of the unit cell, r_w is the equivalent radius of the drain, r_s is the radius of the smear zone, and q_w is the discharge capacity of the drain.

The distribution of excess pore water pressure (u) in the radial direction (r) at a given time (t) is:

$$u = \frac{\gamma_w}{2k}\left[r_e^2 \ln\left(\frac{r}{r_w}\right) - \frac{r^2 - r_w^2}{2}\right]\frac{\partial \varepsilon_v}{\partial t} \quad (4)$$

where γ_w is the unit weight of water, and $\partial\varepsilon_v/\partial t$ is the volumetric strain rate, which can be expressed by U and initial excess pore water pressure (u_0) as:

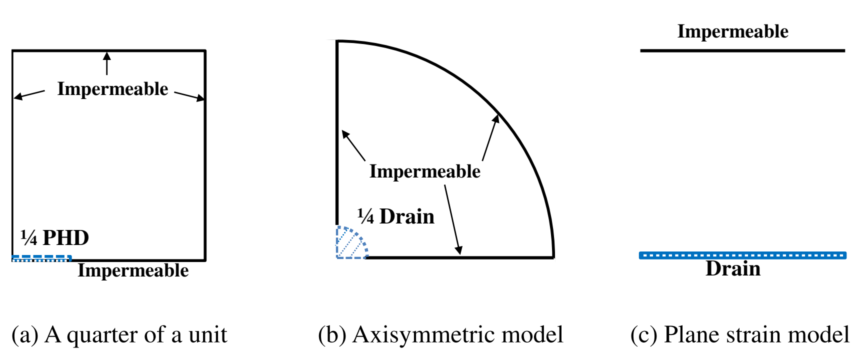

Fig. 2. Models for consolidation analysis.