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Estimation of the hydraulic conductivity of soils improved with vertical drains

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A R T I C L E I N F O

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A B S T R A C T

In this study, some limitations associated with modeling the hydraulic conductivity of soil improved with vertical drains are discussed. In addition, some limitations of conventional methodologies for deducing the hydraulic conductivity from oedometer or Rowe cell tests are investigated. An alternative approach for estimating the hydraulic conductivity in soils improved by vertical drains is discussed. This methodology will allow for simpler finite element modeling of consolidation due to vertical drains. The effectiveness of this technique has been demonstrated using a field study.

1. Introduction

The use of vertical drains (e.g., prefabricated vertical drains – PVDs) is one of the most popular and economical methods for improving soft soils. Vertical drains shorten the drainage path and accelerate consolidation. Thus, when used in combination with preloading, vertical drains enhance the soil bearing capacity and post construction soil deformation over a relatively short period. For most soft soil deposits, the horizontal hydraulic conductivity (K_h) is higher than the vertical hydraulic conductivity (K_v) [1,2], which also promotes faster consolidation.

In the classical solution of consolidation due to a single vertical drain, the zone of influence of the drain, which is also known as the unit cell, is approximated as a cylinder of soil with the drain at its center [2,3]. An idealization of the unit cell is presented in Fig. 1. To model consolidation in the vertical drain improved soil, knowledge of the hydraulic conductivity (K) and the extent of the smear zone due to drainage installation are required. These parameters are difficult to determine accurately and are known to vary with the size and shapes of the mandrel (e.g., circular, rectangular, rhombic) and also with the end plate design. The hydraulic conductivity of the soil in a smear zone (K_s) equal to K_v (a constant value along the radial direction) has been recommended by Hansbo [4]. However, researchers agree that K_s is not a constant parameter and varies with the distance from the drain [5–7]. For design purposes, several researchers [4–6,8–13] have recommended using 1–5 times "equivalent mandrel diameter" as the extent of the smear zone. To date, the choice of this number has largely depended on personal experience. The estimated K may also vary subjectively. Thus, exact modeling of the smear zone (the extent of smear zone and K_s through laboratory or field tests) may be complicated, time consuming, expensive and have a high degree of uncertainty.

Laboratory oedometer tests are widely used in industry to determine K_v of soils. However, the interpretations of these tests require underlying assumptions that are often overlooked. For example, the conventional method of deducing K_v from an oedometer test is based on the assumption that the soil conforms to a linear stress–strain relationship. However, this assumption is not true for many soil types. The deduced K may change if a different material behavior is considered. Thus, the deduced K, even from laboratory tests, may depend on the constitutive model and is not an independent number. This issue will be explored in a later section of this paper.

The Rowe cell test can be used to deduce the K_h values, but the issue regarding the soil stress strain relationship remains. This issue coupled with the additional uncertainties that are associated with the extent of the smear zone and the K_s make consolidation modeling of soil improved by vertical drains more challenging.

This paper investigates the effectiveness of some of the conventional techniques for deducing the K of soils. Some limitations have

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been discussed in light of a series of numerical analysis results. In addition, an alternative, simpler and objective approach for modeling the consolidation due to vertical drain, and a related K value that avoids explicit modeling of the smear zone is discussed. Furthermore, an example field case is presented to demonstrate the effectiveness of the technique.

2. Interpretation of the laboratory test data for estimating hydraulic conductivity

The oedometer test is one of the most common and popular tests conducted in the geotechnical industry. This test provides information about the compressibility and K_v of soils. The coefficient of consolidation is estimated using a transformed plot of void ratio (e) or settlement versus time (using the square root or the logarithm of time for the abscissa) from laboratory consolidation data. A coefficient of consolidation (C_v) is deduced from the transformed time–settlement (or e) plot and the K_v is deduced using the following relationship.

$$K = C_v \frac{a_v}{1 + e_{av}} \gamma_w \tag{1}$$

Here, γ_w is the unit weight of water, e_{av} is the average e during consolidation and a_v represents the linear stress–strain relationship. In this case, the methodology is based on a constant volumetric compressibility (or stress–strain relationship).

Thus, K_v is deduced from a back-estimate that depends on the soil stress–strain relationship. Similar approximation is made in the Rowe cell tests, which can also be used for deducing K_h. Thus, the following question remains: is the K deduced from the displacement–time curve dependent on the assumed stress–strain relationship?

To investigate this question, synthetic time settlement curves (for the oedometer and Rowe cell lab tests) were simulated using finite element (FE) analyses with non-linear soil models and input K values. Next, the generated time–settlement curves were interpreted using the conventional techniques discussed above, and the results were compared with the input values.

The input K can either be a constant (denoted as C) or vary with the void ratio e (denoted as V). In the latter case, the following function proposed by Taylor [14] is adopted:

$$\log K = \log K_i - \frac{(e_0 - e)}{C_k} \tag{2}$$

Here, K is linked to the void ratio e, K_i is reference hydraulic conductivity for the reference void ratio e_0, and C_k is the slope of the $K - e$ plot when K is plotted in log scale on the vertical axis.

Two different types of soil models were used for this investigation.

- The modified Cam Clay (MCC) model [15].
- An elastic viscoplastic (EVP) model that models secondary compression as creep and uses a nonlinear creep coefficient, as proposed by Karim et al. [16].

Thus, an analysis can be denoted as X-YYY, where X refers to the type of K (constant or variable with e) and YYY refers to the soil model type. For example, V-MCC denotes a simulation conducted with varying K (in accordance with Eq. (2)) and using the MCC soil model. The simulation assumptions and input parameters in this investigation represent the assumed soil characteristics. The input soil parameters are presented in Table 1. The last two columns of soil parameters, $C_{\alpha max}$ and N, are only needed for modeling the creep coefficient in the EVP model described by Karim et al. [16].

2.1. K_v from the simulated oedometer test

The simulated oedometer sample was 63 mm in diameter and 19 mm thick. An idealization of the modeled geometry with boundary conditions is presented in Fig. 2. Axisymmetric analyses were conducted using the FE computer program AFENA [17]. Only half of the geometry was modeled because of axial symmetry. Overall, 48 six-nodded triangular elements with 117 nodes were used.

The simulated loading histories include the following:

- an initial vertical stress of 20 kPa and
- the stress was doubled at every load step over a duration of 24 h.

The maximum stress used in the oedometer simulations was 640 kPa. For each loading step (i.e., 40, 80, 160, 320 and 640 kPa), the simulation generates a time–displacement plot. Next, the K_v values were deduced from the simulated displacement–time plots using both log-time and Square-root-time methods (both methods are common in engineering practice). At the stress level of 640 kPa, some of the generated time-deformation curves were not

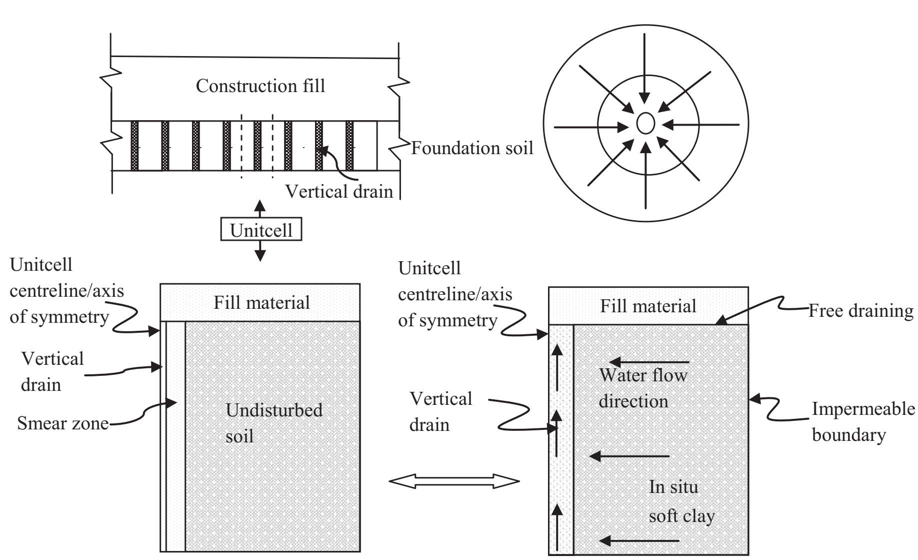

Fig. 1. Unitcell idealization and flow direction of water in a unitcell (not drawn to scale).