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Probabilistic design of ground improvement by vertical drains for soil of spatially variable coefficient of consolidation

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ABSTRACT

The design of soil consolidation via prefabricated vertical drains (PVDs) has been traditionally carried out deterministically and thus can be misleading due to the ignorance of the uncertainty associated with the inherent variability of soil properties. To treat such uncertainty in the course of design of soil improvement by PVDs, more rational probabilistic methods are necessary. In this paper, a simplified probabilistic method is proposed in which the inherent variability of the coefficient of consolidation, which is the most significant uncertain soil parameter that affects the consolidation process, is considered. An easy-to-use design procedure and charts are provided for routine use by practitioners.

1. Introduction

Over the past decade or so, the development activities in areas of soft soils have increased significantly so as to suit the demands of the increased population in many countries and to ensure the marginal use of limited land space. Construction over soft soils often requires a pre-construction treatment of the existing soft subsoils so that soil strength and stiffness are improved, thus, eliminating the undue risks of excessive post construction deformations and associated instability. Among a number of available ground improvement techniques, the use of prefabricated vertical drains (PVDs) with preloading has become the most viable for stabilization of soft soils (Indraratna et al., 2012). PVDs accelerate the consolidation process and prevent post-construction build-up of excess pore water pressure, leading to improved soil strength and reduced lateral and differential settlements (Rowe and Taechakumthorn, 2008).

Despite the fact that the theoretical design aspects of soil consolidation by PVDs are well established (e.g. Barron, 1948; Hansbo, 1981; Hird et al., 1992; Onoue, 1988; Yoshikuni and Nakanodo, 1974), reliable predictions of the soil consolidation rates remain difficult to obtain due to the uncertainty associated with the factors affecting the consolidation process (Hong and Shang, 1998; Rowe, 1972; Zhou et al., 1999). The uncertainty associated with the design of any geotechnical engineering system including soil consolidation can be divided into three main sources (Phoon and Kulhawy, 1999): inherent variability; measurement error and transformation uncertainty. The inherent variability (also called aleatoric uncertainty) is due to the natural geologic processes caused by the complex characteristics of transport of raw materials, layered deposition and common weathering (Vanmarcke, 1977). The measurement error is mainly due to the inadequate equipment and poor testing procedures. The transformation uncertainty (also called model uncertainty) occurs during the translation of the field or laboratory measurements into design, using empirical or correlation models. Collectively, the measurement error and model uncertainty can be described as epistemic uncertainty. To obtain a reliable design for a geotechnical system, all of the above sources of uncertainty should be taken into consideration. However, the measurement error and transformation uncertainty can be reduced or even removed by improving the measurement methods and enhancing the calculation models (Lacasse and Nadim, 1996). Therefore, the inherent variability is the most significant source of uncertainty that needs to be addressed in design of geotechnical engineering systems and this is the main focus of the present paper for soil improvement by PVDs.

The degree of consolidation achieved via PVDs is greatly controlled by some soil properties (e.g. soil permeability and volume compressibility) that are spatially variable and potentially

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induce inherent variability in their characterization, which provides significant geotechnical uncertainty. However, given the analytical and numerical complexity of the problem of soil improvement by PVDs, available research into soil consolidation considering geotechnical uncertainty has been very limited and also failed to accommodate the true nature of inherent soil variability. For example, Hong and Shang (1998) and Zhou et al. (1999) presented a probabilistic design method based on available analytical solutions considering the geotechnical uncertainty associated with the coefficient of horizontal (radial) consolidation. However, this method is inadequate as soil variability was characterized by random values rather than by random fields. Walker and Indraratna (2006) proposed an analytical model based on Hansbo (1981) theory incorporating a parabolic horizontal permeability distribution in the smear zone. Basu et al. (2006) and Abuel-Naga et al. (2012) have extended the work done by Walker and Indraratna (2006) to include a transition zone of linearly varying permeability between the smear and undisturbed zones, but the permeability in the smear and undisturbed zones are assumed to be constant. Therefore, there is a need to develop an alternative probabilistic design method that considers the true nature of soil inherent variability in the course of design of soil improvement by PVDs and this paper will fill in this gap.

In order to include the inherent soil variability in design of soil improvement by PVDs, a computational numerical stochastic scheme that combines the finite element method and Monte Carlo (FEMC) technique can be employed. However, such numerical scheme is complex and requires a large number of simulations that are computationally intensive and time consuming, and it is not uncommon that practicing engineers have neither the time nor the resources to perform such FEMC simulations. Consequently, in this work, an alternative approximate simplified probabilistic design method (PDM) that can be readily used by practitioners is developed in which the inherent soil variability of the coefficient of consolidation is explicitly incorporated in a systematic and economically viable manner. The proposed PDM is verified by comparing its results with those obtained from the FEMC solutions and the results are found to be in good agreement. In the sections that follow, detailed description of the proposed PDM is demonstrated followed by the stochastic FEMC approach. Finally, a comparison between the results obtained from the PDM and FEMC is presented and discussed.

2. Probabilistic design method of soil consolidation by PVDs

The probabilistic design method (PDM) described herein considers, for the first time, incorporation of the true nature of soil variability in design of soil improvement by PVDs. The soil property considered to be randomly variables is the horizontal coefficient of consolidation, c_h, as it is the most significant soil property that affects soil consolidation by PVDs, as explained in the next section. It should be noted that the proposed PDM method is an extension of the previous work done by Hong and Shang (1998) and Zhou et al. (1999) but in the current study the inherent soil variability of c_h is explicitly incorporated and appropriately implemented. The proposed PDM is approximate and can be used to estimate the drain spacing by employing a factored design value of c_h so as to satisfy a specific target probability level of the degree of consolidation that needs to be achieved in a specified timeframe. The proposed PDM involves the following steps:

1. Identification and characterization of soil properties that are spatially variable in the ground;
2. Development of analytical formulation for the design factors taking into account the associated uncertainty due to spatially variable soils;
3. Estimation of correlation structure of soils; and
4. Development of probabilistic design procedure and charts for routine use by practitioners.

Details of the above steps are described and discussed below.

3. Identification and characterization of spatially variable soil properties

As mentioned earlier, spatial variability of soil properties affects the behavior of soil consolidation, and among all soil properties affecting soil consolidation, the coefficient of vertical consolidation, c_v, and coefficient of horizontal consolidation, c_h, are the most significant. Both c_v and c_h may vary substantially in the ground, even in a uniform soil layer (Chang, 1985). For example, based on experimental data, Terzaghi et al. (1996) reported that the coefficient of variation (COV) of c_v for Mexico City clay, San Francisco clay and clay deposit in Pisa (Italy) are 12%, 35% and 69%, respectively. By analyzing c_v values obtained from oedometer tests carried out on Kawasaki clay, Chang (1985) estimated COV of c_v to be 30%. According to data reported by Lumb (1974), the COV of c_v and c_h are estimated to range from 25% to 50%, and based on data reported in the literature, Lee et al. (1983) found that the extent to which c_v and c_h vary may range from 25% to 100%.

As mentioned above, both c_v and c_h exhibit inherent variability and may be considered as random variables in design of soil stabilization by PVDs. However, in accordance with the sensitivity analyses carried out by Hong and Shang (1998) and Zhou et al. (1999) considering several uncertain soil properties, it was found that c_h is the most significant random soil property affecting the degree of soil consolidation by PVDs. In addition, the consolidation of soil by PVDs can take place by simultaneous vertical and horizontal (radial) drainage of water. However, as the drainage length in the vertical direction is significantly higher than that of the horizontal direction and water flow resistance in the horizontal direction is often much lower than that of the vertical direction (Bergado et al., 1993; Hansbo, 1981), soil consolidation due to vertical drainage is much less than that of horizontal drainage. Furthermore, it has been shown by Crawford et al. (1992) from a back-analysis of an instrumented test embankment in Canada that the rates of consolidation are very sensitive to c_h, and that c_h is the most significant design parameter. Accordingly, in the proposed probabilistic design approach, c_h is considered to be the only spatially variable soil property, while the other soil properties are held constant and treated deterministically, including c_v, so as to reduce the superfluous complexity of the problem.

Inherent variability of soil properties can be mathematically characterized by treating the soil properties as random variables. In statistics, a random variable is described by a probability distribution (usually referred to as the 'PDF' or probability density function). The PDF of a random variable can be represented by several classical statistical parameters, namely, the mean value, μ, variance, σ^2 (the variance can also be represented by standard deviation, σ, or COV, υ and $\upsilon = \sigma/\mu$). However, inherent variability of soil properties is not entirely random and spatial dependencies also exist (Fenton and Vanmarcke, 1990; Jaksa et al., 1997; Vanmarcke, 1977). That is, a soil property at two separate spatial locations could be similar or otherwise, depending on the distance they are located apart and this is known as spatial correlation. Vanmarcke (1977) pointed out that adequate characterization of spatially variable soil properties requires consideration (incorporation) of such spatial correlation. The mean and standard deviation are the point statistical measures