Computers and Geotechnics 78 (2016) 171–180

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

Influence of biodegradable natural fibre drains on the radial consolidation of soft soil

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ARTICLE INFO

Article history:
Received 21 August 2015
Received in revised form 24 March 2016
Accepted 12 May 2016

Keywords:
Natural prefabricated vertical drains
Consolidation
Natural fibres
Biodegradability
Discharge capacity

ABSTRACT

Natural prefabricated vertical drains (NPVDs) produced from biodegradable materials such as jute and coir have some distinct advantages over conventional polymeric prefabricated vertical drains (CPVDs). For instance, NPVDs are not only able to discharge excess pore pressure effectively but are also beneficial to the environment thanks to their biodegradability. However, due to the biodegradability of the natural fibres, NPVDs can sometimes deteriorate too quickly in an adverse environment such as in highly acidic clay, which hampers the dissipation of excess pore pressure. In this paper, an analytical solution for radial consolidation that considers the time-dependent decay of drain discharge capacity is therefore proposed. The solution is applied to an exponential form of reduction of the drain discharge capacity, and then verified with the experimental results obtained in previous studies. The effect of drain degradation on soil consolidation is simulated using a finite element method (ABAQUS) and these numerical results are then compared to those obtained from the analytical approach. In addition, a new and flexible method using a matching factor to convert the parameters from axisymmetric to plane strain models is introduced and applied to radial consolidation. The modelling outcomes indicate a significant retardation of excess pore pressure dissipation due to drain degradation and this suggests the need to exercise caution when using biodegradable NPVDs.

1. Introduction

Prefabricated verticals drains (PVDs) which can be considered as one of the most effective methods for improving soft soil have been employed widely in many coastal regions such as Tianjin Port, China [1]; Changi Airport, Singapore [2]; and Second Bangkok International Airport, Thailand [3], but the high consumption of polymeric materials during the manufacture of traditional synthetic PVDs has been blamed for their adverse carbon footprint. Natural prefabricated vertical drains made from fibres such as jute, coir, and straw that are abundant in many developing regions, especially in Southeast Asia, are now emerging as an attractive alternative. Numerous laboratory and field investigations (e.g., [4–6]) have compared NPVDs with CPVDs in terms of robustness, high discharge capacity, and particularly the aspect of biodegradability. The major concern of past studies was to compare the performance of the NPVDs in more inert soft clays that are unlikely to seriously impede their mechanical performance. However, in highly acidic or bio-active soil, natural fibre drains have the potential to degrade much faster than when exposed to more biologically inert soils.

Of the existing natural fibres, jute and coir are the most preferable components for NPVDs due to their favourable engineering properties and low-cost availability in developing countries. Jute and coir fibres are extracted from jute plants and coconut husks, respectively then subjected to a braiding process which has been explained in detail by Rao et al. [7]. A typical prefabricated vertical jute drain includes 3–5 cores made from coir strands enveloped by one or two filter layers of jute burlaps to form a whole drain board of approximately 80–100 mm in width and 8–10 mm in thickness. Coir fibre has approximately 30% lignin [8], which is much higher than for jute fibres. Coir fibre is also more robust and durable than other natural fibres. Jute fibre contains more than 80% cellulose and only around 10% lignin according to Som et al. [9], and that makes the fibre relatively sensitive to adverse environmental conditions.

A considerable number of studies have reported a rapid decomposition of natural fibres in an acidic environment. Som et al. [9] pointed out that jute fibre degrades much faster in an acidic environment having a pH value less than 5.2. Saha et al. [10] also found that the fibre can degrade rapidly in conditions of pH less than 4 or

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http://dx.doi.org/10.1016/j.compgeo.2016.05.013
0266-352X/

Nomenclature

a_w, b_w	width and thickness of the prefabricated vertical drain
b_e	half-width of influence zone in plane strain system (m)
b_s	half-width of smear zone in plane strain system (m)
b_w	half-width of drain well in plane strain system(m)
c_h	coefficient of consolidation for horizontal drainage, $c_h = k_h/(\gamma_w m_v)$ (m^2/s)
f_g	geometric factor, $f_g = r_e/b_e$
k_h	horizontal permeability coefficient of undisturbed zone (m/s)
k_s	horizontal permeability coefficient of smear zone (m/s)
l	length of drain (m)
m	matching factor for conversion procedure
m_v	coefficient of volume compressibility for one-dimensional compression
n	ratio r_e/r_w in axisymmetric condition or b_e/b_w in plane strain condition
q_w	discharge capacity of drain well (m^3/s)
r	distance from centre of drain in axisymmetric unit cell (m)
r_e, d_e	radius, diameter of influence zone (m)
r_s, d_s	radius, diameter of smear zone (m)
r_w, d_w	radius, diameter of drain well (m)
s	ratio r_s/r_w in axisymmetric condition or b_s/b_w in plane strain condition
T_h	dimensionless time factor for horizontal drainage
t	time (s, days)
u	excess pore pressure (kN/m^2)
V	total volume of unit cell
z	depth (m)
α	geometric parameter representing the influence zone
β	geometric parameter representing the smear zone
ε	vertical strain of soil mass
γ_w	unit weight of pore water within soil
λ	parameter representing the permeability of undisturbed soil
$\mu_{n,s}$	parameter representing the geometry of the unit cell including smear and influence zones
μ_q	parameter representing the degradation behaviour of drain discharge capacity
θ	parameter representing the well resistance in the conventional method
ν	Poisson's ratio
χ	parameter representing the influence zone and the coefficient of consolidation
ω	decay coefficient of the exponential degradation function

higher than 9. Particularly, he claimed that only about 10–15% of the residual tensile strength of the jute geotextile remained after 120 days in a medium having a pH value less than 4. Potentially damaging pyritic acidic soils are found in many regions of the world, as reported by Dent and Pons [11]; and Fitzpatrick and Shand [12]. In addition, sulphate-reducing bacteria that is active in pyritic soils as well as other micro-organisms prevalent in organically rich soils can also exacerbate the degradation of natural fibres, as shown by Kim and Cho [6]; and Saha et al. [10].

Although several recent studies, such as those reported by Kim et al. [13] and Deng et al. [14] were concerned with soil consolidation aided by synthetic PVDs exhibiting reduced discharge capacity over time, these studies focused on degradation behaviour due to physical clogging and kinking. NPVDs made from natural fibres are more flexible, and their drainage characteristics are less sensitive to deformation [5]. In addition, NPVDs usually have significantly lower initial discharge capacities [5,15] that might result in a more critical impact on soil consolidation due to the decreasing discharge capacity. More importantly, a specific form of discharge capacity reduction was assigned in those models, which is inapplicable to natural fibre drains that degrade biologically. Therefore, if reliable predictions of consolidation times are required, a comprehensive model capable of capturing soil consolidation incorporating the degradation of NPVD drains is imperative, particularly if they are installed, for instance, in acidic estuarine plains.

In this paper, a general degradation function for drain discharge capacity over time was assumed and incorporated in a conventional analysis of consolidation assisted by PVDs. A closed form mathematical solution was then formulated to describe the radial consolidation of soil, capturing the corresponding reduction of the drain discharge capacity. An application of the method assuming a trend of exponential reduction of discharge capacity was carried out and verified against experimental results. Some microbiological studies have provided evidence of such exponential decay of natural materials attributed to biological attack ([16–20]). The predictions of the proposed analytical method were also compared with those obtained from a numerical approach.

2. Radial consolidation without drain degradation

2.1. Axisymmetric condition

With reference to Barron [21], the governing equation for radial consolidation within a unit cell (Fig. 1a) can be written as:

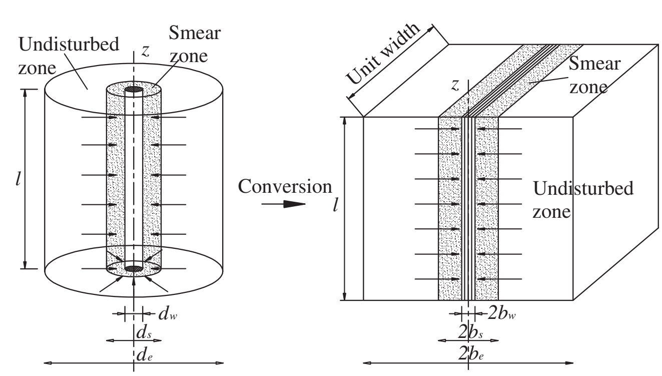
$$c_h\left(\frac{1}{r}\frac{\partial u}{\partial r}+\frac{\partial^2 u}{\partial r^2}\right)=\frac{\partial u}{\partial t} \tag{1}$$

where r is the distance from the centre of the unit cell, u is the excess pore pressure, c_h is the coefficient of consolidation for horizontal drainage, and t is time.

The solution for Eq. (1) can be represented as follows (modified after Hansbo [22]):

$$\frac{\overline{u(t)}}{u_o}=\exp\left(\frac{-8T_{h,a}}{\mu_a}\right) \tag{2}$$

where



(a) Axisymmetric unit cell (b) Plane strain unit cell

Fig. 1. Conversion from axisymmetric to plane strain unit cells.