A Numerical Approach to Model Biodegradable Vertical Drains

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Abstract
Because of their distinct features such as biodegradability and favourable engineering properties, naturally occurring materials including jute and coconut fibres have been used increasingly in numerous geoengineering applications in recent years. However, these materials can sometimes decompose rapidly when subjected to adverse environmental conditions, resulting in severe degradation of their engineering characteristics and consequently causing damage to the design target. This paper presents a numerical approach where the finite-element method (FEM) is used to estimate the influence that the degradation of natural fibre drains can have on soil consolidation. A subroutine which can describe the reduction in drain discharge capacity over time is incorporated into the FEM model. Different cases including those varying the rate and time-dependent form of biodegradation are examined in this paper. The results of this investigation indicate that the dissipation of excess pore pressure can be hampered significantly if drains decay too early and speedily, particularly when the discharge capacity falls below 0.03 m³/d. Different rates of decay can impose different consolidation responses in the surrounding soft soil. Application of the proposed FEM to compare with laboratory data indicates an acceptable agreement between the predictions and the measurements.

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Abstract

Attributed to distinct features such as biodegradability and favourable engineering properties, naturally occurring materials including jute and coconut fibres have been used increasingly in numerous geoengineering applications in recent years. However these materials can sometimes decompose rapidly when subjected to adverse environmental conditions, resulting in severe degradation of their engineering characteristics, and consequently causing damage to the design target. This paper presents a numerical approach where the Finite Element Method (FEM) is used to estimate the influence that the degradation of natural fibre drains can have on soil consolidation. A subroutine which can describe the reduction in drain discharge capacity over time is incorporated into the FEM model. Different cases including varying the rate and time-dependent form of biodegradation are examined in this paper. The results of this investigation indicate that the dissipation of excess pore pressure can be hampered significantly if drains decay too early and speedily, particularly when the discharge capacity falls below 0.03 m\(^3\)/day. Different rates of decay can impose different consolidation responses in the surrounding soft soil. Application of the proposed FEM to compare with laboratory data indicates an acceptable agreement between the predictions and the measurements.
Introduction

Geosynthetics have played an increasing important role in various geoengineering applications such as drainage (Arulrajah et al. 2009; Indraratna et al. 2011; Nguyen and Indraratna 2017b), filtration and reinforcement in soil (Pinto 2003; Indraratna et al. 2006; Chu et al. 2011). However, this approach usually requires extensive use of polymeric materials which are resistant to biodegradation. This is why the application of naturally occurring materials such as jute and coconut fibres has received significant attention in recent decades. Natural fibres do not only have preferable engineering characteristics such as high hydraulic conductivity and tensile strength, they are also biodegradable over time, so they are used to create natural fibre drains (NFDs). Although many previous studies (Lee et al. 1994; Jang et al. 2001; Lee et al. 2003; Asha and Mandal 2012) report that NFDs can perform as well as polymeric prefabricated vertical drains (PPVDs), some indicate that critical degradation of natural fibres can occur as they are exposed to adverse environmental and geotechnical conditions (Miura et al. 1995; Kim and Cho 2008; Saha et al. 2012). While conventional design methods (Barron 1948; Hansbo 1981; Rujikiatkamjorn and Indraratna 2009) normally assume constant drain properties of drains over time, overly swift degradation of NFDs can result in a significant loss in their engineering characteristics, leading to a negative effect on the soil consolidation progress. This issue, therefore, requires a detailed evaluation both in a fundamental and practical sense.

Biodegradation is a natural process in which organic materials (i.e., jute, coconut fibres) are decomposed by microbial activities such as metabolic and enzymatic processes. This would
not occur without microorganisms whose activities vary considerably in relation to surrounding environmental factors such as acidity, temperature and humidity. For example, most bacteria can decompose organic matters more rapidly in warmer climates and also, many organic substances can decay much faster when they are exposed to aerobic conditions (Inglett et al. 2005). Chemical properties of natural fibres are also a key factor determining the rate of decomposition. For example, coconut with more than 40% lignin resists biodegradation far better than jute which has only around 12% lignin (Nguyen et al. 2018).

Considerable effort has been made to evaluate the biodegradation of natural fibre drains over the years. For example Miura et al. (1995) show serious degradation of jute drains installed in Ariake clay where the tensile strength of drains decreased by approximately 80% over a short period of 128 days. Kim and Cho (2008) investigated the degradation of natural fibre drains over different seasons in the field and concluded a considerable reduction in the tensile strength of fibres in warm periods. Indraratna et al. (2016) addressed how the rapid degradation of NFDs could affect the consolidation process using an analytical approach. Although this study has indicated adverse consequences of drain degradation on soil consolidation, it is specific to a given mathematical form, i.e., exponential function of degradation, while the biodegradation in the field is more complex.

The Finite Element Method (FEM) is one of the most preferable solutions to predict soil behaviour induced by vertical drains (Indraratna and Redana 2000; Indraratna et al. 2005; Chai et al. 2013). It has been commonly assumed in previous numerical studies that vertical drains have constant properties such as the diameter and discharge capacity during soil consolidation,
however, this can sometimes cause inaccuracies because of the reduction in drain discharge capacity attributed to large deformation and soil clogging. Furthermore, biodegradation can result in damage of drain porous characteristics which play a primary role in the hydraulic conductivity of natural fibre drains (Nguyen and Indraratna 2016, 2017a). Nguyen et al. (2018) by conducting numerous microscopic observations on porous structure of jute bundles buried in a saturated soft soil show a considerable biomass generated in the pore of drains, leading to a reduction in their discharge capacity. To enable FEM to capture those effects of drain degradation on soil consolidation, conventional approaches need to be significantly improved.

This study presents a modified finite element analysis whereby a subroutine is developed to incorporate the reduced drain permeability into the soil consolidation. This method is then applied to evaluate how the drain degradation can affect the dissipation of excess pore pressure (EPP) considering different biodegradation characteristics.

**Theoretical consideration**

*Modelling assumptions considering biodegradation characteristics of natural fibre drains*

Due to the complexities of biodegradation process of natural fibre drains (NFDs) discussed above, the numerical simulation in this study relies on following key assumptions:

1. The discharge capacity of drains is assumed to decrease over time while other parameters such as the length and diameter of drains are kept unchanged. Also the discharge capacity is expected to decrease to a finite constant level in which natural fibres have been transformed completely into organic soil content (Figure 1).
ii) An initial intact (inactive) period is assumed before the reduction in discharge capacity begins. This is because, microbes such as bacteria and fungi take time to colonise and consume the natural fibres particularly in saturated soils in the absence of oxygen (Inglett et al. 2005; Muyzer and Stams 2008). The duration of this period varies with different environmental conditions as discussed later in this paper.

iii) Unlike purely exponential degradation used by Indraratna et al. (2016) and Deng et al. (2014), the proposed numerical method can be applied to any given time-dependent change of discharge capacity as shown in Figure 1.

iv) The degradation of NFDs can occur earlier and faster at the surface soils because of more aerobic conditions and higher temperature, thus an inhomogeneous degradation over the depth is also captured.

Capturing reduced discharge capacity in finite element analysis

In general, a unit cell (Figure 2) is usually considered to study radial consolidation induced by a vertical drain (Barron 1948; Hird et al. 1992; Indraratna et al. 2005). In this approach, excess pore pressure generated by the applied surface load is assumed to dissipate radially through the vertical drain due to the difference in hydraulic gradient. Also the smear effect caused by drain installation is incorporated into the unit cell by defining a smear zone around the drain.

In finite element method (FEM), the unit cell is discretised into a finite number of elements incorporating the governing equations, i.e., Biot theory (Hibbitt et al. 2012) describing the dissipation of fluid through solid elements under a hydraulic gradient. The 8-node biquadratic displacement and bilinear pore pressure CAX8P elements incorporated in
the software code ABAQUS (2012) are employed in the axisymmetric analysis. In this study, for a unit cell having a radius of 0.5 to 0.6 m and a depth from 10 to 20 m, the size of soil elements varying from 0.025 to 0.1 m provides adequate accuracy. A constant uniform load is placed on the surface of the cell at the initial stage.

Unlike conventional methods in which the discharge capacity and the geometric parameters of drains are considered to be constant over time, modelling biodegradable drains requires those parameters to be updated at every time step. This can be implemented by using USDFLD subroutine which enables characteristics of materials to be externally managed. In the current study, a subroutine made on Fortran depicting the variation in drain permeability over time was created and coupled with the consolidation analysis (Figure 3). By doing this, various reduction forms of drain discharge capacity can be incorporated, unlike the past analytical methods (Kim et al. 2011; Deng et al. 2014; Indraratna et al. 2016) which are only applicable to a specific form of degradation.

In this study, the discharge capacity \( q_w \) of drain is assumed to be proportional to its hydraulic conductivity \( k_w \) while the cross-area \( A_w \) of the drain remains unchanged as follows:

\[
q_w(t) = k_w(t) \times A_w
\]  

(1)

where the \( k_w(t) \) presents the degradation in hydraulic conductivity of the drain over time. It can be in the form of either a mathematical function with time or tabulated data recorded over time. This is obviously a flexible approach because it is not always possible to have an exact mathematical form of degradation which is usually complex as explained above.
Because the current study concentrates on the dissipation of excess pore pressure, a simple elastic model is employed to describe soil deformation. A coefficient of volume compressibility $m_v = 0.005 \text{ m}^2/\text{kN}$ and Poisson’s ratio $\nu = 0$ which ensures no lateral displacement and a uniform deformation in the unit cell, are used in the numerical analysis. The equivalent diameter of the drain is calculated by $d_w = 2(a+b)/\pi$ where $a$ and $b$ are the thickness and width of the drain (Hansbo 1979; Chu et al. 2004). Jute drains commonly include 4 to 5 coir strands wrapped by 1 to 2 layers of jute burlaps. Their thickness normally varies from 8 to 12 mm while the width changes from 80 to 110 mm; giving an average diameter $d_w = 70 \text{ mm}$ which is larger than a typical polymeric PVD, i.e., 50 mm.

The smear zone of unit cell is calculated based on Indraratna and Redana (1998), whereby the ratio $d_s/d_w$ varies from 3 to 4. Because jute drains can be installed in the same way as conventional wick drains (i.e., a metal mandrel with anchors), hence a ratio $d_s/d_w$ of 3.4 is assumed. This study also assumes an influence zone of $d_e = 0.6 \text{ m}$ and a treatment depth of 20 m. The horizontal permeability $k_h$ in the undisturbed soil zone is $5 \times 10^{-9} \text{ m/s}$ while the ratio between the permeability in the undisturbed and smear zones ($k_h/k_s$) is 3.0. The initial discharge capacity i.e., $q_w = 0.43 \text{ m}^3/\text{day}$ of jute drains is obtained from previous studies (Nguyen et al. 2016; Nguyen et al. 2018). Pore water is not allowed to flow through the boundary of the unit cell except to the surface of the drain. Pore pressure is obtained at different nodes of elements, and the average value over the unit cell is then computed accordingly.
Results and discussion

Effect of biodegradation on soil consolidation

Compared to conventional method with different rates of degradation

How the reduction in discharge capacity of drains influences the dissipation of excess pore pressure (EPP) is presented in Figure 4. Compared to the conventional case where the discharge capacity is constant (continuous line), the dissipation of EPP is retarded considerably. For example, while the drain without degradation results in complete dissipation of EPP after approximately 400 days, for case 1 where the discharge capacity decreases to $3 \times 10^{-4}$ m$^3$/day after 500 days still has around 8% EPP remaining. In fact, the EPP of case 1 begins to deviate from the no-decay curve after about 80 days where the discharge capacity reduces to approximately 0.1 m$^3$/day. Note that in this figure, the reduction in discharge capacity which is induced by reducing the permeability of drain elements in FEM is presented.

This numerical simulation also indicates that the more rapid the degradation is, the more serious can be the retardation in the EPP dissipation. Four cases representing varying degree of degradation are shown Figure 4a. While case 1 shows the slowest degradation where the discharge capacity reaches $3 \times 10^{-4}$ m$^3$/day after 500 days, case 4 presents the fastest reduction in discharge capacity, i.e., $1 \times 10^{-7}$ m$^3$/day after the same duration. As a result of this, the corresponding residual values of EPP are 8 and 22% for cases 1 and 4, respectively. Cases 2 and 3 have degradation rates in between cases 1 and 4, resulting in residual EPP of 11 and 18%, respectively. In addition, case 4 begins to deviate from the conventional curve earlier (i.e., at 50 days) than the other 3 cases.
Fig. 4 also indicates there is a threshold level of discharge capacity in which the dissipation of EPP is being prevented severely. In this study, the critical value of \( q_w \) is found to be approximately 0.03 m\(^3\)/day, and for those periods before reaching this critical value, the differences between the consolidation curves are not significant. For example, as shown in Figure 4, the discharge capacity of case 4 reaches 0.03 m\(^3\)/day after nearly 95 days at which its corresponding value of \( u(t)/u_o \) is about 6% larger than that determined by the conventional consolidation curve (continuous line). Note that this value varies with different soil properties and the size of the unit cell such as the diameter and the treatment depth. Also note that the dissipation of EPP can become nearly insignificant at small discharge capacity. For example at approximately 200 days in case 4 where the dissipation curve is almost horizontal if the discharge capacity of drain has reached a very small level, i.e., 0.002 m\(^3\)/day.

Influence of different forms of degradation

There is a considerable difference in response of soil consolidation to different ways and rates of change in discharge capacity. Figure 5a shows two types of degradation: one begins as soon as the drain is exposed to adverse soil conditions, while the other describes an initial delay period where the degradation of the drain is insignificant. In these two situations, \( q_w \) decreases to the same level after the same duration, i.e., \( 2.65 \times 10^{-6} \) m\(^3\)/day after 600 days albeit decaying at different points. An intact period of 60 days is assumed in this analysis based on previous biological studies into the decomposition of cellulose materials in anaerobic soils (Leschine 1995; Inglett et al. 2005). Note that case B with a delay period has a larger decay rate to ensure it reaches the same final value as the immediate reduction in case A. Figure 5b shows how soil
consolidation responses to different degradation forms, i.e., cases A and B as shown in Figure 5a. Immediate degradation results in a higher residual EPP (i.e., 11%) compared to only 4% in the delay period (case B) after 300 days. In fact, the two curves begin to deviate from each other after approximately 80 days and the gap becomes larger towards the end of the study period. Unlike the analytical method presented by Indraratna et al. (2016) which requires a particular mathematical form of degradation to be incorporated into the governing equation of consolidation, the proposed numerical solution is more flexible when considering any form of discharge capacity reduction trends.

Compare to analytical methods

In this section, the proposed numerical method is compared to analytical methods described by Deng et al. (2014) and Indraratna et al. (2016). While Deng et al. (2014) consider an exponential reduction in the permeability of drains to solve the governing equation by an approximation method, Indraratna et al. (2016) propose a more general approach using an overall degradation function of discharge capacity \( q_w(t) \). However to obtain an exact solution, Indraratna et al. (2016) still require a particular degradation form, for example an exponential reduction form of \( q_w(t) \), i.e., \( q_w(t) = q_{wo} \times e^{-\omega t} \) where \( \omega \) is the decay coefficient representing the rate of reduction in discharge capacity per a unit time. In the current study, \( q_{wo} = 0.43 \text{ m}^3/\text{day} \) and \( \omega = 0.02 \text{ day}^{-1} \) are used to compare with the FEM analysis while other properties of the soil and drain are the same as previous sections.

Figure 6 shows the results obtained from the current numerical method (FEM) in comparison with the analyses by Deng et al. (2014) and Indraratna et al. (2016). There is a
good agreement between these studies, particularly in the first 140 days when the excess pore pressure predicted by all methods decreases by approximately 67%. The numerical simulation begins to deviate from analytical methods after 150 days. For example, the residual EPP given by FEM is nearly 18% which is lower than those (i.e., 22%) obtained using analytical methods at 300 days. This figure indicates an acceptable accuracy of numerical prediction in comparison to the independent analytical approaches.

Influence of varying biodegradation over depth

Soil properties such as the temperature, water content and other biological characteristics vary considerably along the depth. Figure 7 presents a typical case where the upper soil layer causes a faster degradation of natural fibre drains caused by the greater concentration of oxygen and higher temperature. This study assumes the degradation occurs only at the upper layer \( l_d \) while the remaining part of the drain is still intact. A treatment depth of 20 m is considered with \( l_d \) varying from 1 to 10 m. The degradation curve of the drain is shown in Figure 8a over 500 days with almost no decay during the initial 30 days.

Figure 8 shows how varying the thickness \( l_d \) can influence the dissipation of excess pore pressure in the unit cell. When \( l_d \) is small enough, i.e., less than 1 m, the effect of drain degradation on the dissipation of EPP is insignificant; particularly it results in approximately 3% difference in EPP compared with the one without degradation. However it begins to deviate considerably from the no-decay curve as \( l_d \) becomes larger. For example the difference in EPP reaches nearly 14% after 500 days when \( l_d \) increases to 5 m. It is also noteworthy that this deviation does not increase much when \( l_d \) continues to rise up; in fact it increases to only
16% when \( l_d \) doubles from 5 to 10 m. This indicates the drain which degrades partially at surface depth can lead to a considerable retardation of the overall dissipation of EPP when the soil layer affected by drain degradation is thick enough.

**Application to an experimental study**

In this section, the proposed numerical method is used to compare with an independent laboratory study (Kim et al. 2011) where a reduced drain discharge capacity was recorded over time. In this laboratory investigation, a large block sample of the soft soil from a depth of 12.0 to 14.0 m in a field near the new port at Busan (South Korea) was placed into 1.2 m diameter by 2.0 m deep cell for a radial consolidation using a vertical drain. This experimental scheme used a drain with \( d_w = 5.0 \) cm and an estimated smear ratio of \( d_s / d_w = 6 \). The initial discharge capacity of the drain installed into the block samples under a vertical pressure of 300 kPa was approximately 5.0 m\(^3\)/year (0.014 m\(^3\)/day) which was much smaller than those measured through the discharge capacity test without any soil. For example using a small cell for testing resulted in a discharge capacity larger than 438 m\(^3\)/year (Kim et al. 2011). Figure 9a shows the time-dependent discharge capacity recorded during the consolidation test. Note that Kim et al. (2011) used a wide range of the drain hydraulic conductivity, i.e., \( k_w = 5 \times 10^{-7} \) to \( 1 \times 10^{-6} \) m/s.

Some of the soil properties described by Kim et al. (2011) are uncertain; for example while there is a lack of soil properties used in the laboratory consolidation test, the study assumes soil parameters with reference to the profile of a certain soil layer in the field. To clarify those parameters, a back-analysis on the consolidation curve using their semi-analytical solution was carried out, giving a consolidation coefficient \( c_h \) of 0.155 m\(^2\)/day. The coefficient
of permeability $k_h = 3.6 \times 10^{-10} \text{ m/s}$ and the ratio $k_h/k_s = 2.0$ were assumed with respect to the soil properties in the field as reported by Kim et al. (2011). A finite element analysis using the Fortran subroutine to capture the reduction in discharge capacity was also carried out. Figure 9b shows how the unit cell established in FEM to mimic the consolidation test is being meshed using quadrilateral elements.

The numerical results (Figure 10) show how the degraded drain can make the dissipation of excess pore pressure deviate significantly from the one without degradation. The gap between the degraded and non-degraded curves becomes apparent after 7 days as the discharge capacity decreases to a level smaller than 0.003 m$^3$/day. As the discharge capacity of drain decreases more pronouncedly after 10 days, the dissipation ratio $u(t)/u_0$ induced by degradable drain is almost 10% larger than the drain for which the drainage properties do not change. Figure 10 also shows a comparison between the dissipation of EPP predicted by the finite element method and the experimental data. The difference between the two approaches is insignificant, i.e., less than 2%, which indicates an acceptable accuracy of the numerical (FEM) prediction. Note that while the experimental data was recorded for only nearly 21 days (500 hours), the numerical analysis provides an extended prediction up to 24 days.

**Conclusion**

In this study, a numerical analysis based on the finite element method (FEM) capturing the biodegradation of vertical drain was incorporated into examining soil consolidation. Although there are a number of limitations such as the lack of biodegradation data for drains installed in the field, the following conclusions can still be withdrawn:
1. The reduction in discharge capacity induced by the degradation of drains can seriously hamper the dissipation of excess pore pressure, particularly when the discharge capacity decreases to value below 0.03 m³/day. The faster the degradation, the larger the residual excess pore pressure (EPP). The residual EPP can eventually reach to more than 20% due to pronounced degradation. Differences in the degradation forms, i.e., the immediate vs delayed degradations could make a considerable deviation, for example 7% in their corresponding soil consolidation curves after 250 days.

2. Partial degradation of drains can also result in considerable retardation to the average consolidation progress. When the thickness of the decayed layer was relatively small (i.e., less than 1 m), the retardation in pore pressure dissipation was insignificant, however the residual EPP could increase to 14% if the degraded depth approached 5 m. This suggests an important need for early investigation into near-surface zones where microorganisms can be more active due to a larger concentration of oxygen and higher temperature thereby causing more damage near the soil surface.

3. In comparison to the experimental data that explains how the reduction in drain discharge capacity affect soil consolidation progress, the proposed numerical approach indicated a good agreement. The FEM results also matched with those obtained in previous analytical approaches using exponential degradation form, which indicated an acceptable accuracy of the proposed numerical method.
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Figure 1. Varying reduction behaviour of drainage characteristics of natural fibre drains
Figure 2. Unit cell of vertical drain and finite element modelling

- Uniform surface load
- Undisturbed zone
- Smear zone
- Drain
- Smear zone
- Undisturbed zone

CAX8P Element (Quadratic Interpolation)

- Displacement node
- Pore pressure node

\[ d_w : \text{equivalent diameter of drain} \]
\[ d_s : \text{diameter of smear zone} \]
\[ d_i : \text{diameter of influence zone} \]
\[ l : \text{length of drain (treatment depth)} \]
Figure 3. Algorithm of incorporating reducing permeability into the consolidation of soil

Start analysis

Initial conditions

Apply loads

Start step $i$

Update material properties

Subroutine USDFLD
$k_w(t) = f(k_{w0}, t)$

where
$f(k_{w0}, t)$ is the time-dependent function
$k_w$ is the hydraulic conductivity of drain
$k_{w0}$ is the initial hydraulic conductivity of drain

Solve governing equations

Coupling { Stress-strain analysis
Pore fluid diffusion analysis

Save output

Conditions satisfied?

Yes

End

No

Time step increment $i = i + 1$
Figure 4. Influence of reduced discharge capacity on soil consolidation: a) different rates of degradation; b) corresponding retardation in the dissipation of excess pore pressure

- Critical level
- Conventional method (no decay)

- Case 1
- Case 2
- Case 3
- Case 4

- $k_h = 5.0 \times 10^{-9} \text{ m/s}$
- $k_h/k_s = 3.0$
- $m_v = 0.005 \text{ m}^2/\text{kN}$
- $d_e = 0.6 \text{ m}; d_s/d_w = 3.4 \text{ m}; l = 20 \text{ m}$

- $u(t)/u_0 (%)$
Figure 5. Influence of different degradation forms on soil consolidation: a) two ways of reduction in discharge capacity; b) the corresponding retardation in dissipation of EPP

\[ k_p = 5.0 \times 10^{-6} \text{ m/s} \]
\[ k_h/k_s = 3.0 \]
\[ m_s = 0.005 \text{ m}^2/\text{kN} \]
\[ d_o = 0.6 \text{ m}; \quad d/d_o = 3.4 \text{ m}; \quad l = 20 \text{ m} \]
Figure 6. Compare to other analytical studies

- Current study (Numerical)
- Indraratna et al. 2016 (Analytical)
- Deng et al. 2014 (Analytical)

- $k_n = 1.0 \times 10^{-9}$ m/s
- $k_l/k_s = 3.0$
- $m_v = 0.05$ m$^2$/kN
- $d_e = 0.6$ m; $d_s = 0.24$ m; $l = 20$ m
**Figure 7.** Difference in degradation behaviour of drain along the installation depth
Figure 8. Influence of the partial degradation in drain on soil consolidation: a) degradation curve of drain; and b) the corresponding dissipation of EPP over different decay thicknesses.
Figure 9. FEM modelling of degraded vertical drain in a laboratory study by Kim et al. (2011)
Figure 10. Retardation in the dissipation of EPP predicted by FEM compared with experimental data.