Modelling natural prefabricated vertical drains

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MODELLING NATURAL PREFABRICATED VERTICAL DRAINS

A thesis submitted in fulfilment of the requirements for the award degree

(Thesis by Compilation)

Doctor of Philosophy

from

University of Wollongong

by

Trung Thanh Nguyen

(also known as Thanh Trung Nguyen)

March 2018
DECLARATION

This is to certify that work presented in this thesis was done by the author, unless specified otherwise, and that no part of it has been submitted in a thesis to any other university or similar institution.

This thesis was prepared in the compilation style format based on published journal articles listed in Thesis Related Publications. The bibliographic citation and current status of each journal article were also shown at the beginning of each single chapter. All related journal articles were researched and written during the course of the author’s candidature. Despite a certain level of repetition between chapters in introductory material, each single chapter was substantially different in focus and content within the scope of the thesis theme.

Trung Thanh Nguyen

01\textsuperscript{th} March, 2018
ABSTRACT

Natural prefabricated vertical drains (NPVDs) made from natural fibres such as jute and coir have some promising engineering properties and they are rapidly emerging as a suitable alternative to conventional polymeric drains. Although environmentally friendly natural fibre drains were first introduced almost 30 years ago, they have not been used widely due to their limited supply and our limited understanding of their complex flow characteristics. This thesis, therefore, aims to clarify those issues and suggest practical designs and solutions to expedite their manufacturing capacity.

The influence that biodegradation of NPVDs has on soil consolidation is addressed, and an analytical method in which the biodegradation of NPVDs is incorporated in conventional soft soil consolidation is also discussed. The results from the current analytical solutions are then compared to a numerical approach where a subroutine captures the degrading permeability of drains with time. The proposed solution is then verified with previous studies that demonstrate how the reduced discharge capacity of drains affects consolidation. In addition, a laboratory investigation into the biodegradation of NPVDs installed in different saturated soils is also carried out. The degradation of fibre properties is recorded and genomic and micro-analyses are carried out on decayed fibres to properly understand the biochemical activities of a soil-drain system. This study indicates that soil consolidation can be seriously hampered when natural fibre drains decay rapidly in adverse environments.

A series of experimental investigations into the hydraulic behaviour of fibre drains is carried out, followed by post-processing of the fibre drains in order to understand how microcharacteristics can affect their hydraulic properties. These results are then used to validate the Carman-Kozeny geohydraulic theoretical method in relation to the hydraulic conductivity of
Abstract

fibres. A novel numerical approach is then proposed in which fibres are modelled by the Discrete Element Method (DEM) and the corresponding fluid flow is described by Computational Fluid Dynamics (CFD), an effort is also made to model natural fibres by bonding individual particles in DEM. Apart from conventional bond models, i.e., Parallel Bond Model, a modified version which can capture the nonlinear stress-strain behaviour of natural fibres is also proposed. The results of this numerical work are then compared to the results from the experimental data and previous studies where significantly different solutions were used bonded on other concepts. This study indicates that CFD-DEM coupling is a powerful and cost-effective approach to model natural fibre drains with respect to fluid-particle interaction.
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**Papers in Preparation**


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$A_b$ area of bond
$A_o$ specific surface
$a$ subscription denoting axisymmetric condition
$a_c$ contact area of particles
$a_v$ coefficient of variation
$a_w, b_w$ 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)
$C_d$ fluid-particle drag coefficient
$c_h$ coefficient of consolidation for horizontal drainage, $c_h = k_h / \gamma_w v_m$ (m$^2$/s)
$c_s$ shape factor
$D$ displacement
$d_i$ diameter of particles $i$
$d_{f,i}$ diameter of fibre $i$
$d_h$ pore hydraulic diameter
$F(n)$ function of $n$ representing the size of influence zone
$F_b$ bond force
$F_{bo}$ buoyancy force
$F_c$ contact force
$F_d$ drag force
$F_f$ total fluid-particle interaction force
$F_g$ gravitational force
$f_g$ geometric factor, $f_g = r_e / b_e$
$f_p$ mean volumetric particle-fluid interaction force
$G$ shear modulus
$I_b$ moment of inertia of bond
$I_i$ moment of inertia of particle $i$
$i_h$ hydraulic gradient
$J_b$ polar moment of inertia of bond
$K$ permeability
$k_k$ Kozeny constant
List of Symbols

\( k_h \)  
horizontal permeability coefficient of undisturbed zone (m/s)

\( k_s \)  
horizontal permeability coefficient of smear zone (m/s)

\( k_{bn} \)  
normal stiffness of bond

\( k_{bs} \)  
shear stiffness of bond

\( L(t) \)  
time dependent well resistance

\( l \)  
length of drain (m)

\( M_b \)  
 bond moment

\( M_c \)  
contact torque

\( m_f \)  
matching factor for conversion procedure

\( m_i \)  
mass of particle \( i \)

\( m_v \)  
coefficient of volume compressibility for one-dimensional compression

\( n \)  
ratio \( r_e/r_w \) in axisymmetric condition or \( b_d/b_w \) in plane strain condition

\( n_f \)  
porosity of fibrous media

\( n_p \)  
number of particles

\( p \)  
pressure

\( q_w \)  
discharge capacity of drain well (m\(^3\)/s)

\( r \)  
general radius

\( r_{e, d_e} \)  
radius, diameter of influence zone (m)

\( r_{s, d_s} \)  
radius, diameter of smear zone (m)

\( r_{ws, d_w} \)  
radius, diameter of drain well (m)

\( R_i \)  
radius of particle \( i \)

\( R_b \)  
radius of bond

\( Re \)  
Reynolds number

\( s \)  
ratio \( r_e/r_w \) in axisymmetric condition or \( b_d/b_w \) in plane strain condition

\( S \)  
 spacing of drains

\( T_h \)  
dimensionless time factor for horizontal drainage

\( t \)  
time

\( t_o \)  
tortuosity of flow

\( U_f \)  
velocity of fluid

\( U_p \)  
velocity of particle

\( U_s \)  
superficial velocity of flow

\( u \)  
pore pressure (kN/m\(^2\))

\( V \)  
total volume of unit cell

\( Y \)  
Young’s modulus

\( z \)  
depth (m)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>geometric parameter representing the influence zone</td>
</tr>
<tr>
<td>$\beta$</td>
<td>geometric parameter representing the smear zone</td>
</tr>
<tr>
<td>$\beta_b$</td>
<td>coefficient of the modified Parallel Bond Model</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>time step</td>
</tr>
<tr>
<td>$\Delta x$</td>
<td>the size of fluid cell</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>vertical strain of soil mass</td>
</tr>
<tr>
<td>$\gamma_w$</td>
<td>unit weight of pore water within soil</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>parameter representing the permeability of undisturbed soil</td>
</tr>
<tr>
<td>$\lambda_b$</td>
<td>bond radius multiplier</td>
</tr>
<tr>
<td>$\mu_{n,s}$</td>
<td>parameter representing the geometry of the unit cell including smear and influence zones</td>
</tr>
<tr>
<td>$\mu_q$</td>
<td>parameter representing the degradation behaviour of drain discharge capacity</td>
</tr>
<tr>
<td>$\mu$</td>
<td>summation of $\mu_q$ and $\mu_{n,s}$</td>
</tr>
<tr>
<td>$\mu_f$</td>
<td>viscosity of fluid</td>
</tr>
<tr>
<td>$\rho_f$</td>
<td>density of fluid</td>
</tr>
<tr>
<td>$\rho_p$</td>
<td>density of particle</td>
</tr>
<tr>
<td>$\sigma_b$</td>
<td>normal stress of bond</td>
</tr>
<tr>
<td>$\tau_b$</td>
<td>shear stress of bond</td>
</tr>
<tr>
<td>$\eta$</td>
<td>viscous stress tensor of fluid</td>
</tr>
<tr>
<td>$\theta$</td>
<td>rotational displacement</td>
</tr>
<tr>
<td>$\theta_w$</td>
<td>parameter representing the well resistance</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Poisson’s ratio</td>
</tr>
<tr>
<td>$\nu_k$</td>
<td>kinetic viscosity</td>
</tr>
<tr>
<td>$\chi$</td>
<td>parameter representing the influence zone and the coefficient of consolidation</td>
</tr>
<tr>
<td>$\psi$</td>
<td>factor representing the presence of other particles in a cell</td>
</tr>
<tr>
<td>$\Omega_{p,i}$</td>
<td>angular velocity of particle $i$</td>
</tr>
<tr>
<td>$\psi$</td>
<td>power factor in determining drag force</td>
</tr>
<tr>
<td>$\omega$</td>
<td>decay coefficient of the exponential degradation function</td>
</tr>
<tr>
<td>$\omega_i$</td>
<td>weight factor</td>
</tr>
</tbody>
</table>
Chapter 1 INTRODUCTION

1.1 General

Synthetic materials have been used widely in many geoengineering applications such as geogrids, geocells and geotubes for reinforcement (Bergado and Jin-Chun, 1994; Rowe and Li, 2005; Chu et al., 2011; Indraratna et al., 2015); geotextiles and geomembranes for separation (Rowe and Sangam, 2002; Palmeira et al., 2005); and synthetic prefabricated vertical drain (SPVDs) for drainage (Bergado et al., 1996; Chu et al., 2004; Indraratna et al., 2005d). However, since these geomaterials are basically made from synthetic polymers such as polyvinyl chloride, polyethylene terephthalate (PET) and polypropylene (Nicholson, 2006), concern from ecological and biological perspectives has been raised because polymeric materials are highly resistant to biodegradation and thus harmful to the natural environment (Gregory and Andrady, 2003). This is why using natural fibres such as jute and coir to manufacture geomaterials has received a lot of attention in recent years; for example, natural prefabricated vertical drains (NPVDs) to improve soft soil (Lee et al., 1994; Venkatappa Rao et al., 2000; Kim and Cho, 2008), and coir fibres to reinforce and stabilise soil (Lekha and Kavitha, 2006; Vinod and Minu, 2010; Artidteang et al., 2015).

Naturally occurring materials such as jute, coir, and straw are abundant in many developing regions, especially South and Southeast Asian countries where soil improvement and stabilisation for infrastructure development are usually in high demand. The major producers of coir fibre are India and Sri Lanka, followed by Thailand, Vietnam, the Philippines, and Indonesia (Ali, 2010), while more than 90% of the world’s jute is manufactured in Bangladesh, India, Thailand, and China (Rahman, 2010). Other natural fibres such as straw, bamboo, and hemp are also easily found in many agricultural regions in Vietnam and Thailand. Therefore, utilising these natural materials for geoengineering
purposes is clearly beneficial to the natural environment and for local economies and societies.

One of the best applications of natural fibres in geoengineering is to create prefabricated vertical drains (PVDs) to improve soft ground. Previous studies (Jang et al., 2001; Lee et al., 2003; Kim and Cho, 2008) have shown that these natural PVDs (NPVD) assist consolidation thanks to their excellent discharge capacity and outstanding resistance to large deformation, but there are still numerous unclarified issues with this type of drain which has hindered its wider application since first being introduced by Lee et al. (1984). For example, although most field observations report that biodegradation does not affect the performance of NPVDs, those studies were carried out on inert soils while most soft soils, particularly alluvial and marine soils, have a large organic content and complicated biological properties. Furthermore, the hydraulic behaviour of NPVDs usually varies in porous structures, and since this is not understood very well, their design has been found difficult.

The question of how to optimise the structure and material of a drain to achieve the best engineering properties, including the discharge capacity and biodegradable resistance, has not been given serious attention, which means there is an urgent need to improve our understanding of these promising drains and broaden their application in practice.

This thesis aims to address the biodegradation of NPVDs, evaluate how this aspect of NPVDs can affect consolidation, and also clarify the micro hydraulic properties of natural fibre drains made from jute and coir. To achieve those goals, an experimental approach combined with analytical and numerical methods is used. In the experimental section, hydraulic tests are carried out on jute, coir fibres, and a complete drain meanwhile a long term observation on the basis of biological and microscopic analyses is conducted onto the biodegradation of prefabricated vertical jute drains (PVJDs) buried in saturated clay. An analytical solution predicting the consolidation of soil with respect to the biodegradation of
drains is proposed; the results of which are then validated with experimental and numerical methods. Finally, a novel numerical approach based on a fluid-solid coupling concept is applied to model natural fibre drains.

1.2  **Soil improvement by prefabricated vertical drains**

Prefabricated vertical drains (PVDs) have been used worldwide to improve soft ground, particularly in alluvial and coastal regions. Vertical drains generally imply that a number of soil improvement methods such as sand drains, sand compaction piles, gravel (stone) columns, and PVDs are used, all of which enable pore water to dissipate radially around the central drain. Of those vertical drains, synthetic PVDs (SPVDs) have become more popular than others in recent years because they are based on synthetic polymeric materials which can be produced on a large scale, and they are more convenient to install in the field. Although SPVDs such as band shaped and circular formats exist, the most common one usually has a plastic core which is actually channelled boards wrapped with an unwoven geotextile filter (Fig. 1.1). With this simple format, SPVDs can be produced in large numbers, making it a very economically attractive option in practice.

![Fig. 1.1 Typical synthetic prefabricated vertical drains (http://www.geoengineer.org)](http://www.geoengineer.org)

In practice, PVDs are usually installed with a mandrel which is actually a metal bar to drive the drain down to the desired depth. This mandrel drain can be pressed down with either a static force or a dynamic hammer. Note that the method of installation can cause a
significant variation in the smear zone which is generated when installing the drain. Because PVDs have much larger permeability than soft soil, pore pressure in the soil is discharged through a vertical drain system which then accelerates consolidation. Fig. 1.2 represents a typical installation rig where PVDs are connected to a sand blanket which functions as a horizontal drainage facilitator. In most field applications, surcharge preloading is usually added onto the surface ground to further speed up consolidation.

![Diagram of PVD installation rig](image)

**Fig. 1.2** A typical system using PVDs to improve soft soil (Indraratna et al., 2005d)

On the basis of a conventional vertical drain approach, numerous modifications are now used to enhance the solution, such as PVDs assisted by vacuum preloading and PVDs combined with dynamic compaction. In these novel techniques, PVDs still play a major role in discharging the pore water, while additional components such as vacuum preloading and dynamic compaction are used to accelerate pore pressure dissipation. This indicates that although a huge effort has been made to boost the efficiency of ground improvement technology over the past years, PVDs are still an irreplaceable solution.
1.3 Natural prefabricated vertical drains

While most PVDs are based on synthetic polymers, natural prefabricated vertical drains (NPVDs) are rapidly emerging as a promising alternative to conventional SPVDs. The most common form of NPVDs normally includes one to two layers of jute geotextiles (jute burlap) functioning as the filter, with 4 to 5 coconut cores (Fig. 1.3). Because jute is the major component in this type of NPVD, it is also referred to as Prefabricated Vertical Jute Drain (PVJD), and although NPVDs have various structures and materials, they are all a combination of individual fibres arranged to allows pore water to flow through. While the structure of NPVDs is complex and the number current studies addressing their hydraulic properties is limited, particularly their interaction with clay soil, laboratory investigations (Venkatappa Rao et al., 2000; Jang et al., 2001; Asha and Mandal, 2012) into the discharge capacity of NPVDs have indicated that their discharge capacity is less than SPVDs but still large enough to dissipate excess pore pressure for soil to consolidate.
Natural fibres are cell walls composed of stem and leaf parts that normally consist of cellulose, hemicelluloses, lignin, and aromatics, waxes and other lipids, and ash and water-soluble compounds (Mussig, 2010). There are natural fibres such as jute, coir, straw, and hemp which can be used to generate NPVDs (Fig. 1.4). For fibres extracted from plants such
as jute and hemp, the non-fibre fraction of the plant stem is normally subjected to a process called retting which helps loosen and separate the bast fibre bundles. Other techniques such as drying, carding, spinning and so on are further processed into bast fibre bundles depending on the particular requirements of the final product. The extraction process for other fibres such as coir and straw can be different. Note that the extraction process can affect the tensile strength and durability of fibres while other manufacture techniques such as braiding mainly determines the price of the product. This is why improving the manufacturing technology is a key to making natural fibres more attractive to geoengineering practice.

Since one of the earliest applications of NPVD was carried out in Singapore (Lee et al., 1984), there has been an increasing number of projects in East and South Asian countries such as Malaysia (1989), Singapore (1994), Japan (1995) and Korea (2008) (Lee et al., 2003; Kim and Cho, 2008) using NPVDs to improve soft soil. Although the NPVDs used in those projects varied in their structure and material, they almost succeeded in accelerating consolidation.

Despite the advantages of NPVDs described above, their application is still limited in practice, probably due to:

(i) The biodegradation of NPVDs is obviously good for the natural environment but they can decompose rapidly in environments where cellulose degrading bacteria are present; this has a negative effect on the consolidation of soil, which then means that conventional approaches which do not consider drain degradation when predicting consolidation must be re-evaluated.

(ii) There is a lack of studies which describe how natural fibre drains operate in saturated soft soil. Previous studies (Lee et al., 1994; Jang et al., 2001) showed that NPVDs performed well without significant biodegradation during consolidating while several field observations (Miura et al., 1995; Kim and Cho, 2008) indicate there was a severe
decomposition of jute drains. This controversy has hindered the wider application of these types of drains.

(iii) These drains are slow to mass produce because of high labour costs which means they are less attractive economically than synthetic PVDs which can be mass produced by polymers.

(iv) NPVDs vary considerably in their material and structure, but the question of which has the best discharge capacity and manufacturing proficiency has not been clarified; this leads to a lot of confusion with regards to their application.

(v) Most existing numerical methods can only model fluid flow through pre-formed porous media by assuming unchanged porous characteristics, whereas in practice there are variations during fluid flow due to fluid-particle interaction which results in inaccurate predictions.

Therefore, in order to enhance the use of NPVDs in practice these limitations must be overcome, and that is the major goal of this thesis.

1.4 Objectives and scope of study

Considering the existing problems surrounding NPVDs, this study seeks to achieve the following objectives:

a) Evaluate how the biodegradation of NPVDs can affect consolidation and suggest how caution should be exercised in practice. Establish solutions to enable designs that will capture the influence that biodegradation has on radial consolidation of soil.

b) Investigate the biodegradation of NPVDs in saturated soft soil where drains are most likely to be applied in order to understand the biological mechanism of biodegradation and clarify which condition can cause a serious degradation of drains; this is very important when applying them in the field.

c) A study to clarify how micro-characteristics such as the size, shape, and twisting
angle and porosity of NPVDs can affect their hydraulic properties (discharge capacity). Based on this fundamental understanding, suggests ways to optimise the structure and material of fibre drains.

d) Establish a novel numerical approach that can capture the fluid-fibre interaction and corresponding variation of porous properties while fluid is flowing. This computational scheme will provide a platform to predict the discharge capacity of drains while considering the various porous characteristics.

1.5 **Organisation of the thesis**

Apart from the Introduction contained in this chapter, this thesis includes the following chapters:

- Chapter 02 is a literature review which summarises previous studies of Natural Prefabricated Vertical Drains and other related analytical and numerical methods applied in this study. This includes previous laboratory and field observations on the hydraulic behaviour of NPVDs and soil consolidation; different structures and materials used to make NPVDs; a theoretical consideration of conventional consolidation induced by vertical drains; and other numerical methods such as Finite Element Method (FEM), Discrete Element Method (DEM) and Computational Fluid Dynamics (CFD).

- Chapter 03 describes an analytical approach used to predict the consolidation of soil with respect to the biodegradation of NPVDs. The reduction in discharge capacity of drains due to biodegradation is incorporated into the governing equations of soil consolidation. In addition, the Finite Element Method (FEM) with support from a subroutine which considers the biodegradation of fibre drains is implemented; the results of this numerical method are then validated with the proposed analytical solution.
Chapter 04 describes a laboratory study into the biodegradation of Prefabricated Vertical Jute Drains (PVJDs). In this work, a number of sample PVJDs are buried in saturated soft clay with different acidic magnitudes; the samples are then removed and subjected to tensile tests and genomic and microscopic analyses after certain periods to determine the biodegradation and its biological mechanism.

Chapter 05 contains a series of laboratory investigations into the hydraulic behaviour of natural fibres. Hydraulic conductivity tests are carried out on elemental fibre drains made from jute and coir, followed by post-processing to determine the micro-properties of the drains. Through this scheme, the influence the micro-features have on the hydraulic conductivity of drains is analysed.

Chapter 06 focuses on a novel numerical approach using DEM, CFD, and their coupling concept to model fibrous material. This chapter explains how to apply DEM to model fibrous material while coupling with CFD to predict the hydraulic properties. The numerical results are validated to previous studies using experimental, analytical, and numerical methods.

Chapter 07 is an advanced development based on the numerical scheme shown in Chapter 06. In this chapter, a modified bond model incorporated into DEM framework is proposed to describe the nonlinear stress-strain behaviour of natural fibres such coconut coir. Intensive micro-analysis is carried out to capture the micro-characteristics of coir drains; this information is then used to build a 3 dimensional model of the drain in DEM. The numerical results, including hydraulic conductivity, are validated with experimental data.

Chapter 08 concludes the research achievements in this study with implications for geoengineering practices and suggestions for further studies on the basis of the outcomes of this current thesis.
Chapter 2 LITERATURE REVIEW

2.1 History and development of natural prefabricated vertical drains

The earliest application of NPVDs in the field was reported by Lee et al. (1984) in Singapore where drains made from jute and coconut fibres were used, and over the following 30 years, a lot of effort has been put into developing and widening the practical use of this type of drain. Lee et al. (1994) developed a schematic view of the first fibre drain (Fig. 2.1) which consisted of two layers of burlap (jute geotextile) wrapped around 4 coconut coir strand cores which stiffened the drain. This drain was stitched along its length to separate the coir strands and maintain its form; it was 80 to 100 mm wide and 5 to 10 mm thick. Porosity in these drains is mainly from the jute fibres which is why they are known as prefabricated vertical jute drains (PVJDs). After this introduction, PVJDs composed of jute and coir fibres have become the most preferred type of natural fibre drain because jute and coir are abundant in many developing regions and they have good engineering characteristics.

Fig. 2.1 Schematic view of the NPVD used in Singapore (Lee et al., 1994)

In a later study Venkatappa Rao et al. (2000) examined the engineering properties of a braided strip drain composed of 16 coir cores covered by a layer of braided jute yarns (Fig.
2.2); this drain was 97 to 98 wide and 8 to 10.5 mm thick. By adopting braided technology in the production of this drain, manufacturing time was shorter than previous fibre drains and their designs were more flexible.

![Diagram of braided drain sheath](image1)

**Fig. 2.2 Structure of braided drain sheath (Venkatappa Rao et al., 2000)**

Jang et al. (2001) introduced a circular drain in which a bundle of twisted coir fibres are encased by two layers of jute filter (Fig. 2.3). This structure is much simpler than any band shaped NPVDs, and is faster to manufacture.

![Diagram of circular fibre drain](image2)

**Fig. 2.3 Circular fibre drain (Jang et al., 2001)**

In a pilot project where NPVDs made from straw and jute fibre were installed in parallel to conventional SPVDs in the field (Kim and Cho, 2008). Unlike previous jute drains (Fibre Drain Board-FDB), the straw drain board (SDB) used strands of straw as the core instead of coir but jute burlap was still used for the filter. The core strands made from coconut and straw were 5 and 8 mm in diameter, respectively. In this investigation, the
discharge capacity of the straw drain board was less than the fibre drain board and conventional SPVDs, but it was still enough to ensure the same degree of settlement in the field.

![Image of fibre drain board (FDB) and straw drain board (SDB)]

Fig. 2.4 Natural PVDs used in a pilot project, Korea (Kim and Cho, 2008)

Asha and Mandal (2012) compared the discharge capacity of different NPVDs under varying confining pressures in a laboratory investigation; here 4 types of NPVDs (Fig. 2.5) were examined: NPVD 1 was a conventional format composed of 5 coir strands and woven jute filter; NPVD 2 had the same coir strands but used a non-woven jute sheath as the filter; NPVD 3 was made from flat coir mat encased by a woven jute sheath; NPVD 4 was a corrugated coir mat covered by a woven jute filter.

![Image of varying structure of NPVDs used by Asha and Mandal (2012)]

Fig. 2.5 Varying structure of NPVDs used by Asha and Mandal (2012)

Typical NPVDs used in previous years are listed in Table 2.2 and show the large variations in drain structures. This table also reveals the research carried out over recent
decades to find the most reliable and effective format for NPVDs; even though the results are still being debated, particularly from a manufacture perspective. Because natural fibres are various and abundant, a comprehensive study to clarify which materials are best and how they can best be combined to optimise the discharge capacity is urgently required.
<table>
<thead>
<tr>
<th>Name</th>
<th>Filter</th>
<th>Core</th>
<th>Width x thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVJD provided by the National Jute Board of India</td>
<td>1 layer of jute geotextile</td>
<td>4 Coir strands</td>
<td>100x8</td>
</tr>
<tr>
<td>(used in the current study)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Fibre Drain (NFD)- (Lee et al., 1994)</td>
<td>2 layer of woven jute</td>
<td>4 Coir strands</td>
<td>100x10</td>
</tr>
<tr>
<td>Braided Strip Drain (BSD)- (Venkatappa Rao et al., 2000)</td>
<td>1 layer of jute triaxially braided sheath</td>
<td>16 Coir strands</td>
<td>(97-98)x (8.0-10.5)</td>
</tr>
<tr>
<td>Fibre drain (FD1)- (Jang et al., 2001)</td>
<td>2 layers of woven jute (circular shape)</td>
<td>Coir strings, D(31-33) mm</td>
<td>Diameter 33 mm</td>
</tr>
<tr>
<td>Fibre drain (FD2)- (Jang et al., 2001)</td>
<td>2 layers of woven jute</td>
<td>3 Coir strands, D7.5 mm</td>
<td>108x7.5</td>
</tr>
<tr>
<td>Straw drain board (SDB)- (Kim and Cho, 2008)</td>
<td>1 layers of woven jute</td>
<td>4 Straw strands, D8.0 mm</td>
<td>95x10</td>
</tr>
<tr>
<td>Fibre drain board (FDB)- (Kim and Cho, 2008)</td>
<td>1 layers of woven jute</td>
<td>4 Coir strands, D5.0 mm</td>
<td>85x5</td>
</tr>
<tr>
<td>NPVD1- Asha and Mandal (2012)</td>
<td>1 layer woven jute, 700g/m², 1.8mm thick</td>
<td>Coir strand, D5 mm</td>
<td>90x9</td>
</tr>
<tr>
<td>NPVD2- Asha and Mandal (2012)</td>
<td>1 layer non-woven jute, 680g/m², 8mm thick</td>
<td>Coir strand, D5 mm</td>
<td>90x11</td>
</tr>
<tr>
<td>NPVD3- Asha and Mandal (2012)</td>
<td>1 layer woven jute, 700g/m², 1.8mm thick</td>
<td>Flat coir mat, 10 mm thick</td>
<td>90x12</td>
</tr>
<tr>
<td>NPVD4- Asha and Mandal (2012)</td>
<td>1 layer woven jute, 700g/m², 1.8mm thick</td>
<td>Corrugated coir mat, 13mm thick</td>
<td>90x16.5</td>
</tr>
</tbody>
</table>

Table 2.1 Summary of structural detail of NPVDs made over more than 20 years
2.2 Engineering characteristics of NPVDs

2.2.1 Chemical properties of natural fibres

Since the chemical characteristics of natural fibres determine their engineering properties such as tensile strength and biodegradation, understanding these fundamental quantities is very important. Although many natural fibres can be used to make NPVDs, a lot of them have the same fundamental chemical components such as cellulose, hemicellulose, pectin, and lignin (Mussig, 2010). Cellulose is a linear polymer of glucose and is the most prolific component found in natural fibres; this is closely followed by hemicellulose, a collective term for a very heterogeneous group of polysaccharides. Lignin is a major contributor to the strength, rigidity, and biodegradation resistance of natural fibres; other minor components are fats, waxes, lipid, ash and water-soluble compounds.

<table>
<thead>
<tr>
<th>Fibre</th>
<th>Cellulose (%) range (most frequently published)</th>
<th>Hemi-cellulose (%) range (most frequently published)</th>
<th>Lignin (%) range (most frequently published)</th>
<th>Pectin (%) range (most frequently published)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jute</td>
<td>51-84 (65)</td>
<td>12-24 (15)</td>
<td>5-14 (10)</td>
<td>0.2-4.5 (1.5)</td>
</tr>
<tr>
<td>Coir</td>
<td>32-53 (40)</td>
<td>0.2-0.3 (0.2)</td>
<td>40-45 (43)</td>
<td>3-4 (3)</td>
</tr>
<tr>
<td>Hemp</td>
<td>57-92 (70)</td>
<td>6-22 (16)</td>
<td>2.8-13 (6)</td>
<td>(0.8-2.5 (1)</td>
</tr>
<tr>
<td>Rice straw</td>
<td>28-70 (49)</td>
<td>-</td>
<td>12-16 (14)</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2.2 Chemical properties of common natural fibres (Mussig, 2010)

Table 2.2 shows the chemical components of typical natural fibres such as jute, coir, hemp, and rice straw which are commonly used to create natural fibre drains. Obviously cellulose is the largest component of those fibres, particularly jute and hemp, with 65 and 70%, respectively. This chemical component accounts for around 40% and 49% of coir and
rice straw, respectively. Lignin makes up approximately 10% of jute and hemp but makes up 43% of coir. Note the wide deviation in chemical components given by different studies, as Table 2.2 shows.

2.2.2  Tensile strength

To resist the pull force generated during installation, a drain must have sufficient tensile strength. Most investigations indicate that the tensile strength of NPVDs made from jute and coir varies from 2.5 to 6.6 kN (Lee et al., 1994; Venkatappa Rao et al., 2000), which is more than the strength needed for installation (i.e., 1 kN) suggested in previous studies (Rawes, 1997). The straw drains used by (Kim and Cho, 2008) had a smaller range of tensile strength, i.e., 1 to 3 kN but installation in the file indicated they still satisfied the requirements.

2.2.3  Discharge capacity

Since the main function of PVD is to dissipate excess pore pressure (EPP) and accelerate soil consolidation, the discharge capacity of drains is their most important parameter. Many studies set out to enhance understanding the hydraulic properties of NPVDs, for example Lee et al. (1994) carried out a laboratory test to determine the axial and filter permeability of a jute fibre drain; Venkatappa Rao et al. (2000) conducted discharge capacity tests of braided strip drains, and (Jang et al., 2001) made a laboratory investigation into the discharge capacity of circular and band shaped NPVDs. Despite the different testing models and NPVDs used in those studies, the results generally indicated a promising discharge capacity to accelerate consolidation. The following literature review regarding discharge capacity is represented with respect to the NPVDs shown in Table 2.1 above.
Venkatappa Rao et al. (2000) reported a discharge capacity of 40 to 55 ml/s (3.5 m³/day) for NPVDs in an unconfined condition, but when subjected to a confining pressure of 50 kPa, the discharge capacity decreased to 12 and 22 ml/s for BSD and NFD (Table 2.1), respectively. These values in fact were slightly lower than SPVDs which normally have a discharge capacity of 30 to 50 ml/s at 50 kPa confining pressure (Rawes, 1997). Moreover, Venkatappa Rao et al. (2000) also showed there was a large reduction in the discharge capacity of NPVDs under increasing pressure, particularly after reaching values under 5 ml/s when the pressure was more than 200 kPa; this differed from SPVDs which were less dependent on the confining pressure (Fig. 2.6).

Fig. 2.6 Discharge capacity over confining pressure (Venkatappa Rao et al., 2000)
Fig. 2.7 Schematic view of discharge capacity test used by Jang et al. (2001)

In other laboratory investigations carried out by Jang et al. (2001) where the discharge capacity test was based on the Delft model (Rawes, 1997), a cylindrical chamber was used to keep the drain vertical (Fig. 2.7), the discharge capacity of NPVDs of 12.68 and 7.29 ml/s for FD1 and FD2 (see Table 2.2) at a confining pressure of 50 kPa was obtained. Compared to the values reported by Venkatappa Rao et al. (2000), they were almost identical considering the same level of pressure (i.e., 50 kPa). This study also showed there was a large reduction in the discharge capacity of drains when the confining pressure was increasing.

Fig. 2.8 Discharge capacity test used by Asha and Mandal (2012)

Asha and Mandal (2012) investigated the difference in hydraulic conductivity of various NPVDs (see Fig. 2.5 and Table 2.2) using the testing method given by ASTM D 4716
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(ASTM D4716, 2008) (Fig. 2.8); this method differed from the one used by Jang et al. (2001) above. In this model, the drain was horizontal and the confining pressure was vertical, unlike the in situ condition where the drain is installed vertically. This study showed that the discharge capacity of the drains (NPVD 1, 2, 3 and 4) varied from 3 to 11 ml/s at 50 kPa confining pressure, and there was a large decrease in the discharge capacity as the confining pressure was increasing (Fig. 2.9); this was not seen in polymeric PVD (PPVD). Moreover, the structure of the drain had an obvious influence on the discharge capacity of NPVDs; for example, NPVD 4 consisted of a stiff corrugated coir mat, so it resisted the confining pressure better than the other drains, resulting in the highest discharge capacity.

![Discharge capacity graph](image)

Fig. 2.9 Discharge capacity test at hydraulic gradient $i = 1$ (Asha and Mandal, 2012)

While most studies used a simple laboratory model test where the drain does not make contact with the soil to evaluate its discharge capacity, (Kim and Cho, 2008) investigated this parameter using the composite discharge capacity test where a drain can be installed in a cylindrical soil under a surcharge; in this approach, the discharge capacity can be obtained while the soil is consolidating. This test was carried out on fibre (jute and coir) and straw drain boards (see Fig. 2.4). Under a surcharge pressure of 250 kPa, the stable discharge capacity for fibre and straw drains was 4.6 and 0.77 ml/s, respectively; this showed that the discharge capacity of straw drains compared to jute and coir fibre drains is limited (Fig.
2.10). The discharge capacity obtained in this study was also much smaller than those reported in other studies because the pressure was higher and there was interaction with the soil. This study also showed that in the initial stages, the discharge capacity of all the drains decreased rapidly.

Fig. 2.10 Discharge capacity of NPVDs observed in the field (Kim and Cho, 2008) (re-plotted)

Although most previous studies indicated that NPVDs in different structures and materials have enough discharge capacity to dissipate excess pore pressure, only the macro-hydraulic behaviour of the whole drain was considered, not the micro-properties. For example, the insightful mechanism of fluid flowing through a natural fibre drain and the influence that the micro-characteristics of material and structure have on the hydraulic behaviour of the drain has not clarified; this limits the extension of NPVDs to different natural materials and prevents the drain structure from being improved. A detailed investigation into these limitations is therefore essential.

2.2.4 Biodegradation behaviour

Unlike SPVDs, biodegradation is the unique feature of NPVDs, making them more valuable. After installation, NPVDs decompose due to microorganisms such as fungi and bacteria, so the final product of this biodegradation process is the organic components of soil.
This is very good for the natural environment but if degradation is too fast, consolidation is retarded because the drain cannot dissipate excess pore pressure. This is why several studies into the biodegradation of natural fibre drains have been carried out in recent years.

![Graph showing degradation in tensile strength of NPVDs](image)

Fig. 2.11 Degradation in tensile strength of NPVDs (Kim and Cho, 2008) (re-plotted)

Most field observations (Lee et al., 1994; Lee et al., 2003; Kim and Cho, 2008) indicate that NPVDs degrade in saturated soil over time, but degradation does not influence consolidation induced by the drain. Lee et al. (1994) showed that NPVDs made from jute and coir could work well in the first 2 years subjected to Singapore soft clay. Kim and Cho (2008) investigated the biodegradation of FDB (jute and coir) and SDB (jute and straw) (see Fig. 2.4) installed in the clay of Mokpo, Korea. Their results (Fig. 2.11) showed that SDB degraded faster than FDB, followed by a rapid reduction in tensile strength at later stages. Their study also reported a variation in degradation rate over different seasons; for example, degradation was more severe in spring and summer because the microorganisms are usually more active due to a higher temperature; but despite this reduction in tensile strength, consolidation had not really been affected.

Saha et al. (2012) addressed the degradation of jute fibres subjected to different conditions while considering the physical, biological, and chemical parameters separately. Their study showed a rapid decrease in the tensile strength of jute fibres exposed to media.
having a pH lower than 4 or higher than 9 (Fig. 2.12a). Note that for the chemical impact, this study put the fibres into inorganic acidic and alkaline liquids which did not evaluate any biological properties of the media. To consider the biodegradation, jute fibres were placed into a medium made from organic garden soil, sand, and cow dung; the jute fibres (JGU-jute geotextile untreated) decayed completely after only 120 days (Fig. 2.12b). Although this study created ideal conditions where particular chemical or biological factors were considered individually, it indicated the potential for extremely severe degradation that jute fibres could experience in a certain medium.

![Graphs of chemical and biological degradation](image)

**Fig. 2.12 Degradation of jute fibres exposed to different media (Saha et al., 2012)**

In a particular case where jute drains were installed in Ariake saturated clay, Japan (Miura et al., 1995), here they lost almost 80% of their initial tensile strength after only 126 days of consolidation (Fig. 2.13); this is the most severe degradation of NPVDs recorded since first being introduced in 1984. This result also indicated that NPVDs can decay seriously when they are exposed to adverse media.
Although most studies did not report any significant degradation of NPVDs during consolidation, some natural fibre drains still showed some rapid decomposition. No study has really clarified the conditions under which the biodegradation of natural fibre drains can become serious enough to affect consolidation, which is why a study to obtain a biological insight into the biodegradation of natural fibres is important.

2.3 Soil consolidation induced by vertical drains

2.3.1 Mechanism of vertical drain induced consolidation

In a system where vertical drains are used to improve soft soil, drains made from highly permeable materials such as PVDs, sand, and stones to facilitate the drainage of pore water are installed vertically to make a radial drainage unit cell. Here, pore water in the surrounding soil under compression (e.g., loading) is mainly discharged radially through the drain due to the difference in hydraulic gradient and conductivity instead of vertical drainage in a system without drains; this helps to shorten the drainage and increase the dissipation rate of excess pore pressure (EPP).
This mechanism of radial consolidation was first shown schematically by Barron (1948) (Fig. 2.14). According to this theory, the cylinder unit cell at the centre of the drain has a diameter $d_e$ (radius $r_e$) which represents the drainage influence of drain; the drain well has an equivalent diameter $d_w$ while $l$ is the installation depth of the drain, and $S$ denotes the distance between drains. Fig. 2.14 shows a double drainage where the top and bottom surfaces are permeable, but note that most in situ cases only have an upward flow. The characteristics of these parameters are discussed in the following sections.

![Plan of Drain Well Pattern](image)

**Cross-section A-A**

Fig. 2.14 Basic concept of radial consolidation theory (Barron, 1948)
2.3.2 Equivalent diameter of drain well

Although most PVDs are band shaped (see Fig. 1.1), the drain well in radial consolidation theory is usually assumed to be a cylinder with an equivalent diameter $d_w$. A number of approaches such as the equilibrium in area (Fellenius and Castonguay, 1985) or circumference (Hansbo, 1979; Rawes, 1997) and the simplified form by averaging two sides of the drain cross-section (Rixner et al., 1986; Long and Covo, 1994) have been proposed over the past years to determine $d_w$. Because the perimeter of a drain decides the external contact area of drain with soil, it has a greater effect on the discharge capacity; this is why most studies and practices (Rawes, 1997; Indraratna and Redana, 1998; Chai and Miura, 1999; Chu et al., 2004) refer to the perimeter equivalent diameter.

2.3.3 Smear effect

The smear zone is the region immediately surrounding the drain during installation which can cause a significant disturbance to the original soil. This smear effect affects the permeability and lead to different rates of soil consolidation; this is why previous studies put a large effort into determining the size, i.e., $d_s$ and properties of soil in the smear zone.

The size of smear zone is mainly influenced by installation features such as the size of mandrel and the shape of the anchor, so the larger the diameter of the mandrel, the larger the diameter of the smear zone. Bergado et al. (1991) showed that smaller mandrel results in faster settlement and higher amounts of compression because the smear zone is smaller. Since the anchor is normally the first part of the mandrel which touches the soil, its shape can also reduce disturbance to the soil. A mandrel with a closed end can generate greater excess pore pressure on the surrounding soil and cause ground heave and lateral displacement. The driving speed during installation can also disturb the soil in different ways.

Laboratory investigations have reported a considerable variation in the size of the smear zone; for example Hansbo (1979) estimated the ratio $d_s/d_w$ from 1.5 to 3 while Bo et
al (2000) proposed that the $d_s/d_w$ varies from 5 to 8. Other studies suggest this ratio should be around 2 (Bergado et al., 1991) or 3-4 (Indraratna and Redana, 1998). These differences are probably due to differences in the soil and the approaches used for estimation in those studies.

2.3.4 Influence zone

The influence zone is the boundary of radial drainage of the unit cell whose diameter is estimated using installation templates which usually include triangular and square patterns. The diameter of the influence zone for triangular and square patterns is $1.092$ and $1.05$ times the drain spacing $S$ (Rujikiatkamjorn, 2005); the larger the drain spacing, the larger the influence zone, but the lower the consolidation rate.

![Fig. 2.15 Influence zone in different drain well patterns (Rujikiatkamjorn, 2005)]

2.4 Modelling soil consolidation induced by PVDs

2.4.1 Analytical approach

The concept of radial consolidation induced by vertical drains was first discussed almost 80 years ago in several early studies by Carrillo (1941, 1942) and Terzaghi (1943), but a full analytical model which includes the well resistance and smear effects was not introduced until Barron (1948). In this analytical approach, the following assumptions are made: (1) the soil is fully saturated and all the initial vertical loads are carried out by excess
pore water pressure $u$; (2) all the compressive strain is vertical and the applied load is assumed to be uniformly distributed; (3) small strain theory is adopted; (4) Darcy’s law is valid; (5) the permeability of the drain is finite; (6) the influence zone of the drain is assumed to be cylindrical and axisymmetric. The general governing equation for three dimensional consolidation of soil is given by:

$$\frac{\partial u}{\partial t} = c_h \left( \frac{1}{r} \frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial r^2} \right) + c_v \left( \frac{\partial^2 u}{\partial z^2} \right)$$ \hspace{1cm} [2.1]

where $r$ is the distance from the centre of the unit cell; $u$ is the excess pore pressure; $c_h$ and $c_v$ are the coefficients of consolidation for horizontal and vertical drainage, respectively; and $t$ is the time. Considering only horizontal drainage in a unit cell, Eq. [2.1] becomes:

$$\frac{\partial u}{\partial t} = c_h \left( \frac{1}{r} \frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial r^2} \right)$$ \hspace{1cm} [2.2]

Two hypotheses were considered in previous studies, including Barron (1948), and they are as follows:

(i) Free strain assumes that differential settlement which occurs during consolidation over the influence zone has no effect on the redistribution of stresses due to the fill arching.

(ii) Equal vertical strain indicates a situation where the soil adjacent to the drain well consolidates and compresses faster than soil farther away from the drain, which results in different rates of consolidation over the cell.

Barron (1948) showed that the different results between these two cases is insignificant, so a simpler solution using an equal vertical strain assumption is preferred. Based on this approach, Hansbo (1981) proposed a simple solution which incorporated the smear and well resistant effects into the governing equation of radial consolidation as follows.
\[
\overline{u(t)} = \frac{u_o}{\mu_a} = \exp \left( \frac{-8T_{h,a}}{\mu_a} \right)
\]  \hspace{1cm} [2.3]

where

\[
T_{h,a} = \frac{c_{h,a}}{d_w^2}
\]  \hspace{1cm} [2.4]

\[
\mu_a = \frac{n^2}{n^2 - 1} \left[ \ln \left( \frac{n}{s} \right) + \frac{k_{h,a}}{k_{s,a}} \ln(s) - \frac{3}{4} \right] + \frac{s^2}{n^2 - 1} \left[ 1 - \frac{s^2}{4n^2} \right] + \frac{k_{h,a}}{k_{s,a}} \left( \frac{1}{n^2 - 1} \right) \left[ \frac{s^4 - 1}{4n^2} - s^2 + 1 \right] + \pi \frac{2k_{h,a}}{3q_w} l^2 \left( 1 - \frac{1}{n^2} \right)
\]  \hspace{1cm} [2.5]

Here, the subscript \(a\) indicates an axisymmetric condition, \(T_h\) is the dimensionless time factor for horizontal drainage, \(\overline{u(t)}\) is the average excess pore pressure at time \(t\) over different regions in the unit cell, \(u_o\) is the initial excess pore pressure, \(\mu_a\) is a parameter representing the well resistance \(q_w\), smear effect \(s=d_e/d_a\) and influence zone \(n=d_e/d_w\), where \(d_e\) and \(d_s\) are the diameters of the influence and smear zones, \(d_w\) is the equivalent diameter of the vertical drain, \(l\) is the length of the drain, and \(k_h\) and \(k_s\) are the horizontal permeability coefficients of the undisturbed and smear zones, respectively.

This approach is the preferred method for predicting consolidation induced by vertical drains because it is not only simple, it is very reliable. This is why various studies have made an enormous effort to apply this solution to particular cases to achieve higher accuracy. For example, studies (Hansbo, 2001; Sathananthan and Indraratna, 2006; Kianfar et al., 2013) modified the Darcian to non-Darcian concept when considering radial flow in soil with a very low permeability. A research group at the University of Wollongong (Indraratna et al., 2005a; Indraratna et al., 2005d; Rujikiatkamjorn and Indraratna, 2007) introduced vacuum pressure to the conventional method of Barron (1948) and Hansbo (1979), and Indraratna et al. (2005b) incorporated compressibility indices and varying horizontal permeability due to large
strain into radial consolidation. These particular cases are not part of the scope of this study.

In most previous studies, the discharge capacity and equivalent diameter were considered to be unchanged during consolidation because synthetic PVDs, particularly those made in recent years, are very durable. Recent studies (Chu et al., 2004) showed that modern PVDs can resist bending and kinking very well, and therefore have enough discharge capacity for consolidation. However, several observations (Miura and Chai, 2000; Kim et al., 2011) indicate that the discharge capacity of drain can be reduced significantly because the drain is confined by clay and is under a large deformation. This is why several studies (Kim et al., 2011; Deng et al., 2013) propose solutions to predict consolidation with reference to a reduction in the discharge capacity of drains. Kim et al. (2011) modified Yoshikuni and Nakanodo’s (1974) solution to incorporate a reduced discharge capacity into soil consolidation by introducing the following time dependent well resistance:

\[
U_h = 1 - \exp \left[ \frac{-8T_h}{F(n) + L(t)} \right] \tag{2.6}
\]

In the above, \(L(t)\) is the function of well resistance with time and given by:

\[
L(t) = a \times T_h + b \tag{2.7}
\]

where \(a\) and \(b\) are the constants obtained from experimental data. \(F(n)\) is calculated by:

\[
F(n) = \frac{n^2}{n^2 - 1} \ln(n) - \frac{(3n^2 - 1)}{4n^2} \tag{2.8}
\]

This solution is a semi-analytical method where the time dependent well resistance \(L(t)\) is determined based on experimental data which limits the solution

Deng et al. (2013) assumed an exponential function which represents the degradation in permeability, i.e., \(k_w = k_{wo} \exp(-a_w t)\) where \(k_{wo}\) is the initial permeability of a drain well, and \(a_w\) indicates the reduction in permeability per unit time. This degradation is incorporated into the governing equation of radial consolidation (Hansbo, 1981) and the
method of separating variables is adopted; this results in the following approximate solution:

\[
U_r = 1 - \sum_{m}^{\infty} \frac{2}{M^2} \left[ \frac{1 + C_o \exp(-\alpha T_h)}{1 + C_o} \right]^{\frac{8}{\tau F_a}}
\]

where

\[
F_a = \frac{n^2(F_n + F_s)}{n^2 - 1} + \frac{s^2}{n^2 - 1} \left( 1 - \frac{k_h}{k_s} \right) \left( 1 - \frac{s^2}{4n^2} \right)
\]

\[
M = \frac{(2m + 1)\pi}{2}
\]

\[
C_o = \frac{M^2F_a \ n^2}{8G_o \ n^2 - 1}
\]

\[
G_o = \frac{k_h \ l^2}{k_{wo} \ d_{wo}^2}
\]

Although this solution provides a more flexible and accurate approach than the one made by Kim et al. (2011), it uses an approximation method which depends on the number of iterations \( m \) for accuracy. Moreover, this solution has been created specifically for synthetic PVDs where a reduction in the discharge capacity is induced by physical issues such as clogging and bending.

2.4.2 Numerical approach

Finite Element Method (FEM) is the most common numerical method used to simulate soil consolidation over the past years because engineers find it easy to use and it provides reliable results. In this approach, the system of soil and vertical drains is divided into a finite number of elements in which the mechanical governing equations such as the stress-strain relationship and consolidation are solved numerically. In an early study, Hird et al. (1992) indicated that FEM can provide a flexible approach in which to analyse the
influence of reinforcement and staged construction.

FEM was used by Indraratna et al. (1992; 1994) to predict the behaviour of soil due to vertical drains. They incorporated FEM in the CRISP code developed at Cambridge University, UK, to model soft soil at the Muar plain Malaysia that had been stabilised by vertical drains. There was an acceptable accuracy in this prediction, although the deformation predicted by CRISP based on the modified Cam-Clay theory had been overestimated.

Fig. 2.16 Finite element discretisation for CRISP analysis (Indraratna et al., 1992)

Those early works inspired an extensive use of FEM to model vertical drains installed in soft soils, especially in recent years (Indraratna and Redana, 1997, 2000; Indraratna et al., 2005a; Yildiz, 2009; Chai et al., 2013a; Chai et al., 2013b). It is commonly agreed that FEM can capture the dissipation of excess pore pressure very well, as well as the settlement and lateral displacement of soil. Moreover, the response of soil to different stages of construction, such as loading, could also be predicted through this numerical computation.

2.4.3 Plane strain conversion

To reduce the computational load in finite element analysis, the 3-dimensional (3D) model is usually simplified to 2-dimensional (2D) scale. Hird et al. (1992) showed the need to convert parameters from the 3D model to a plane strain (2D) condition to ensure the same outcome because the stress-strain behaviour between the two models differed. Indraratna et
al. (2005a) warned there would be a large deviation in the FEM output when using proper and improper conversions. Fig. 2.14 explains the difference in drainage properties between axisymmetric and plane strain conditions which result in different geometrical parameters. Hird et al. (1992) proposed the following conversion for the input parameters:

\[
k_{h,p} = \frac{2k_{h,a}}{3 \left[ \ln \left( \frac{n}{s} \right) + \left( \frac{k_{h,a}}{k_{s,a}} \right) \ln(s) - \frac{3}{4} \right]}
\]  
[2.14]

\[
q_{w,p} = \left( \frac{2}{n e} \right) q_{w,a}
\]  
[2.15]

where \(k_{h,p}\) and \(k_{h,a}\) are the horizontal permeability in the plane strain and axisymmetric models, respectively; \(k_{s,a}\) is the permeability in the smear zone in axisymmetric conditions; and \(q_{w,p}\) and \(q_{w,a}\) are the discharge capacity of the drain in plane strain and axisymmetric models. If the smear and well resistant effects are ignored, Eq. [2.14] is simplified as follows:

\[
k_{h,p} = \frac{2k_{h,a}}{3 \left[ \ln(n) - \frac{3}{4} \right]}
\]  
[2.16]
conversion to special cases. For example, Indraratna and Redana (1997) improved this conversion by incorporating the influence of smear zone, which was not included in the solution made by Hird et al. (1992). According to this amendment, the relationship between permeability in the two systems is fully described by:

\[
 k_{h,p} = \left[ \frac{\alpha_p + \beta_p \frac{k_{h,p}}{k_{s,p}} + \theta_p (2lz - z^2)}{\ln \left( \frac{R}{s} \right) + \frac{k_{h,a}}{k_{s,a}} \ln(s) - \frac{3}{4} + \pi (2zl - z^2) \frac{k_{h,a}}{q_w}} \right] k_{h,a}
\]  

[2.17]

where \( \alpha_p \), \( \beta_p \), and \( \theta_p \) are the coefficients where the geometric parameters and discharge capacity of a drain are considered. If the smear effect is ignored in Eq. [2.17], Eq. [2.16] is the result. This conversion was used to predict the consolidation of an in-situ project in Malaysia with reasonable success; and it was further validated to case histories such as the Second Bangkok International Airport, Thailand and the Muar clay Embankment, Malaysia (Indraratna and Redana, 2000).

Sathananthan and Indraratna (2006) used the plane strain conversion for radial consolidation by considering non-Darcy flow. Indraratna et al. (2005a) carried out a plane strain simulation by considering the influence of vacuum pressure on radial consolidation. These studies relied on the conversion concept of Hird et al. (1992), indicating a cost effective approach to simplify the numerical computation.

2.5 Hydraulic behaviour of fibrous materials

Because the drain addressed in this study is made from natural fibres, a literature review is needed to clarify the hydraulic behaviour of fibrous media. This section examines previous studies into the hydraulic behaviour of fibrous materials from the perspective of fundamental material engineering and hydraulic mechanisms.
2.5.1 Experimental investigation

Many studies have addressed the hydraulic properties of fibrous media since one of the earliest works by Sullivan (1942). There are two basic models used to determine the hydraulic conductivity of fibrous materials; either unidirectional or radial flow (Sharma and Siginer, 2010). Fluid flow with a low injection pressure is used to ensure the fibres remain static, by controlling either the velocity or pressure of the inlet fluid while the fluid is flowing. The pressure controlled model is preferable (Sullivan, 1942; Williams et al., 1974; Rahli et al., 1997; Rodriguez et al., 2004) due to its simplicity, particularly in manipulating the hydraulic gradient of flow.

Fig. 2.18 The relationship between shape factor and porosity of parallel fibres obtained through experiments (Sullivan, 1942).

In the study by Sullivan (1942), a laboratory investigation into the longitudinal permeability of fibres such as glass, goat wool, and cooper wires, was carried out, it showed the fundamental relationship between the permeability and porosity of fibrous media, and also provided a certain validity to the semi-analytical Kozeny-Carman (KC) method (Carman, 1937). Following this experimental study, many other works were also carried out
on fibres with more complex structures; for example William et al. (1974) considered an aligned fibre bed made from nylon, carbon, and glass, while Rahli et al. (1997) used uniform copper and bronze wires to form a fibre bundle.

In recent decades, more attention has been given to natural fibres because an increasing number of studies concentrated on their hydraulic behaviour. Rodriguez et al. (2004) used a pressured control test to investigate the permeability of jute and sisal; they concluded that mats made from natural fibres such as jute and sisal have a greater permeability than those made from glass fibres. Hamada et al. (2008) used the conventional resin transfer moulding technique to compare the permeability of natural and bleached jute fabrics; their study pointed out the outstanding permeability of natural fibres over beached ones.

2.5.2 Influence of micro-characteristics on hydraulic behaviour

The micro-characteristics of fibrous media such as the size and arrangement of the fibres plays an important role in hydraulic behaviour; this has actually been shown by many previous studies in material engineering and hydraulic mechanism fields (Williams et al., 1974; Ozgumus et al., 2014). However, this fundamental aspect has not been addressed very much in geoengineering; most studies (Venkatappa Rao et al., 2000; Asha and Mandal, 2012) in geoengineering are concerned with macro-characteristics such as the size and shape of a completed drain made from various fibres. Indeed the number of studies which explain how the micro-properties of natural fibres can affect their hydraulic behaviour is strictly limited.

Ozgumus et al. (2014) carried out a thorough literature review and concluded that the shape of fibre and the gap between individual fibres influences its permeability. A number of studies (Gebart, 1992; Nakayama et al., 2007; Tamayol and Bahrami, 2009, 2010) pointed out the difference in the arrangement of fibres, such as those with quadratic and hexagonal patterns which result in varying hydraulic conductivity; this influence decreases as the media
becomes more porous (Fig. 2.19). Chen and Papathanasiou (2007) used a numerical approach to solve the Stokes equation, and showed that the ratio between the diameter of the fibres and the distance between them has a considerable impact on the permeability of fibre bundle. This indicates that to improve the discharge capacity of fibre drains needs a good understanding of micro-hydraulic behaviour.

Fig. 2.19 Influence of fibre arrangement on permeability (Tamayol and Bahrami, 2010)

2.5.3 Modelling hydraulic properties of fibrous materials

A lot of attention has been given to predicting the hydraulic behaviour of fibrous porous media. The analytical method proposed by Kozeny (1927) and later modified by Carman (1937) is the preferred approach due to its computational simplicity (Sullivan, 1942; Gutowski et al., 1987; Gebart, 1992; Rodriguez et al., 2004; Schell et al., 2007).

\[ K = \frac{1}{k_k A_o^2} \frac{n_f^2}{(1 - n_f)^2} \]  

[2. 2.1]

where \( K \) is the permeability; \( n_f \) is the porosity; \( k_k \) is the so-called Kozeny constant which is determined empirically; \( A_o \) is the specific surface of the media defined as the ratio of the
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fluid-solid interfacial surface to the solid volume in a given fluid-solid system.

Fig. 2.20 A review into the variation of $k_k$ over porosity (Xu and Yu, 2008)

Although the KC method is a straightaway approach, it has some limitations. For example, the Kozeny constant $k_k$ is sensitive to the micro-characteristics of the medium (Xu and Yu, 2008; Ozgumus et al., 2014), and this causes it to vary widely, a result that is creates inconvenience for practical engineers. Moreover, previous studies (Choi et al., 1998; Xu and Yu, 2008) have shown that this solution is not as accurate for very dense fibres because $k_k$ varies over a wide range.

Thanks to the rapid development of computer technology, using numerical solutions to model the transport of fluid through fibrous porous media has become popular (Gebart, 1992; Chen and Papathanasiou, 2007; Tamayol and Bahrami, 2008; Yazdchi et al., 2011b); indeed the ability accurately describe the geometric characteristics and corresponding behaviour of fluid is the key advantage of the numerical approach. Various numerical methods based on intensive computational processes have been proposed to solve hydraulic theoretical equations, e.g., the Stokes and Navier-Stokes, the Finite Element Method (FEM) (Yazdchi et al., 2011a, 2012); Boundary Element Method (BEM) (Chen and Papanastasiou, 2007); the
Finite Difference Method (FDM) (Gebart, 1992), and the Finite Volume Method (FVM) (Tamayol and Bahrami, 2008).

Fig. 2.21 Fibres generated by a Monte Carlo procedure and Navier-Stokes equations (see section 2.6.3) solved by FEM (Yazdchi et al., 2012)

Although a lot of effort has been made over the past few decades to capture the hydraulic properties of fibrous materials, most of the current approaches assume the micro-porous parameters remain unchanged, and the fibrous structure of many fibrous materials are sensitive to external forces, i.e., the fluid and confining forces cause variations in the pore characteristics, including inter-fibre distance, porosity, and the effective flow path. Because of this limitation, most current approaches can only estimate the hydraulic conductivity of preformed porous media; they cannot accurately predict those with varying porous structures while the fluid is flowing. Therefore, a framework which can simultaneously simulate fluid-particle systems while considering their mutual interaction is essential.
2.6 Computational Fluid Dynamics—Discrete Element Method coupling

2.6.1 Discrete Element Method (DEM)

The Discrete Element Method (DEM) (also known as Distinct Element Method) is beginning to emerge as a promising approach to simulate various soil problems, particularly granular materials such as rock, ballast, and sand. The principle concept of this method applied to granular material was first introduced by Cundall and Strack (1979) where granular particles are assumed as individual disks in 2 dimensional scale and their motion and contact are governed by mechanical laws such as Newton’s and Hook’s laws. The dynamic parameters such as the velocity and displacement of particles in the computational domain are calculated individually in each step and updated to the next iteration.

The contact behaviour of particles in DEM is usually governed through either a linear or nonlinear displacement-force relationship. Cundall and Strack (1979) used a linear relationship where the contact force and the normal and shear components $F_{cn}$ and $F_{cs}$ are proportional to the overlap between two particles (Hook’s law).

$$\Delta F_{cn,ij} = k_n \Delta D_{n,ij} = k_n U_{p,ij}(\Delta t)$$ [2.18]

$$\Delta F_{cs,ij} = k_s \Delta D_{s,ij} = k_s \Omega_{p,ij}(\Delta t)$$ [2.19]

where the subscripts $n$ and $s$ indicate the normal and shear components, respectively, and $\Delta$ denotes the increment. $F$, $D$, $k$ are the force, overlap displacement, and stiffness, respectively. $U_{p,ij}$ and $\Omega_{p,ij}$ are respectively the translational and rotational relative velocity of particles $i$ and $j$ in the contact. The force components $F_{cn,ij}$ and $F_{cs,ij}$ are activated when the distance between particles $i$ and $j$ become less than the sum of their radii $R_{p,i} + R_{p,j}$.

Of the most common applications of DEM, is modelling the behaviour of material by bonding discrete particles. Various bonding models have been developed over the previous
years, such as the parallel bond model (Potyondy and Cundall, 2004), the smooth-joint contact model (Mas Ivars et al., 2008), and the new nonlinear bond models (Obermayr et al., 2013; Brown et al., 2014). The parallel bond model (PBM) is preferred in those solutions because it is easy to describe the linear stress-strain relationship and brittle fracture of materials such as rock (Potyondy and Cundall, 2004; Cho et al., 2007), cemented sand (Zeghal and El Shamy, 2008), and geogrids (Ngo et al., 2014).

Although the PBM has shown a certain success in previous studies, it does have limitations which hamper its wider application; for instance, it can only predict the linear stress-strain relationship while many materials have nonlinear behaviour, and it cannot capture plastic behaviour and ductile fracture which are very common in geomaterials such as polymer materials and natural fibres such as coconut fibres. Therefore an investigation into the ability of PBM to model natural fibres and the corresponding solution is very much needed.

DEM is currently available in packages such as Particle Flow Code (PFC, 2014), YADE (Kozicki and Donzé, 2009) and LIGGGHTS (Kloss and Goniva, 2010). While PFC is
a commercial product provided by Itasca, YADE and LIGGGHTS are an open source with free access to modify the theoretical background. From a practical perspective, PFC is more convenient because it includes various technical tools and sub-models, and it relies on the Window operating system with a very friendly user interface. However, this package limits users from any in-depth modification of its theoretical background, which makes it difficult for researcher to introduce and include their innovative ideas. This problem can be solved by using open source packages such as YADE and LIGGGHTS which enables users to intervene into the DEM background, particularly in a parallel simulation where DEM can couple with different numerical frameworks. Because the free access approach can enhance the freedom and creativeness in research, it has received far more attention in recent years.

2.6.2 Computational Fluid Dynamics (CFD)

Using computers to simulate fluid dynamic behaviour, particularly as computer technology has developed, is very efficient. Computational Fluid Dynamics (CFD) implies approximation methods to solve sophisticated governing equations which do not usually have exact analytical solutions (Anderson, 1995; Feriger and Peric, 2002). For example, the complete Navier-Stokes equations which describe fluid behaviour with respect to the conservation of mass and momentum cannot be solved analytically in most cases, so the numerical method is a cost effective approach for this problem. Basically, the more complex the problem, the more iteration numbers are needed for the approximation method.

Although numerical schemes can be applied to solve various fluid mechanic theories, the central theory of CFD is normally the Navier-Stokes (NS) equations which fundamentally deal with fluid variables such as fluid velocity and pressure, as follows (Chung, 2010).

\[
\frac{\partial \rho_f}{\partial t} + \nabla (\rho_f U_f) = 0
\]  
[2.20]
\[ \frac{\partial (\rho_f U_f)}{\partial t} + \nabla (\rho_f U_f U_f) = -\nabla p + \nabla \cdot \tau + \rho_f g \]  

[2.21]

where \( U_f \) and \( p \) are the velocity and pressure of fluid; \( \tau \) denotes the viscous stress tensor, \( \rho_f \) is the fluid density, and \( g \) is the gravity constant. Eq. [2.20] represents the conservation of mass while Eq. [2.21] rules the conservation of momentum. Note that these original NS equations are only applicable for incompressible Newtonian fluid.

Of the existing software which provides a CFD platform to simulate fluid behaviour, Open source Field Operation and Manipulation (OpenFOAM, 2014) is preferred in research activities because it has free access and it includes an in-depth theoretical background of fluid mechanics. An extensive range of features to solve various fluid issues, including classical fluid flows and complex fluid behaviours such as chemical reactions, turbulence, and heat transfer, acoustic, solid mechanics, and electromagnetics are all enabled in OpenFOAM. To incorporate the most accurate solution for those various issues in fluid dynamics, the theoretical background in the software is updated every six months with the most recently released and widely accepted scientific researches (http://www.openfoam.com/). This explains why OpenFOAM has a huge user community over other packages.

2.6.3 CFD-DEM Coupling Method

In most geoengineering problems such as erosion, filtration and liquefaction which include two or more phases or interacting sub-systems, a numerical analysis of a single phase or system is clearly not enough, so there is an urgent need to consider multiple phases (Zeghal and El Shamy, 2004, 2008; O’Sullivan, 2011). This is why studies concerning particle-fluid interaction have received a lot of attention in recent years. One of the earliest works carried out by Tsuji et al. (1993) introduced CFD-DEM coupling to 2 dimensional fluidised bed following the locally averaged quantities proposed by Anderson and Jackson (1967). Although this study has limitations such as 2 dimensional scale, and simplified
Navier-Stokes equations and fluid-particle interaction forces, it is a promising approach for simulating multiphase mechanics.

Inspired by the numerical work of Tsuji et al. (1993), an increasing number of studies have been carried out to deepen our understanding of fluid-particle interaction (Hoomans et al., 1996; Xu and Yu, 1997; Kawaguchi et al., 1998). Kafui et al. (2002) made analysed different terms of Navier-Stokes equations and fluid-particle interaction forces, and then pointed out the inaccuracies and limitations of previous studies.

The general scheme used by most CFD-DEM coupling frameworks is shown in Fig. 2.23. Here the properties of particles such as their position and velocity are initially estimated in the DEM platform and then sent to CFD to calculate the fluid behaviour. Conversely, fluid parameters such as the velocity and pressure in individual cells are extracted to calculate the fluid forces acting on particles. This inter-exchange is carried out in every certain number of time steps by regulating how frequently the information between two phases is updated to each other. Note that the original NS equations are modified in this numerical approach by considering the momentum effect of particles on fluid motion, as shown below:

\[
\frac{\partial n_f}{\partial t} + \nabla \cdot (\varepsilon U_f) = 0 \tag{2.22}
\]

\[
\frac{\partial (\rho_f n_f U_f)}{\partial t} + \nabla \cdot (\rho_f n_f U_f U_f) = -n_f \nabla p + \nabla \cdot (n_f \tau) + n_f \rho_f g - f_p \tag{2.23}
\]

where \( n_f \) is the porosity and \( f_p \) is the mean volumetric particle-fluid interaction force. These parameters are added to the conventional NS equations (Eq. [2.20] and Eq. [2.21]) to consider the influence of solid phase (particles) on fluid behaviour. \( f_g \) represents the momentum exchanged from particles (DEM) to fluid dynamics (CFD).
As well as the governing equations of fluid, fluid forces induced due to fluid flowing are introduced to the governing equations of particles in DEM. The conventional governing equation of DEM is then rewritten as follows:

\[ m_i \frac{dU_{p,i}}{dt} = \sum_{j=1}^{n_i} F_{c,ij} + F_{g,i} + F_{f,i} \]  \[ [2.24] \]

where \( F_{f,i} \) is the total fluid forces which can include the drag force, the pressure gradient, the viscous forces, and other unsteady forces such as the virtual, the Basset, and the lift forces (Zhu et al., 2007; Zhou et al., 2010).

There is a massive debate surrounding components of the total fluid force acting on particles. Tsuji et al. (1993) assumed an inviscid flow through fluidised bed and hence only the drag force was considered for simplicity. Several later studies (Xu and Yu, 1997; Kawaguchi et al., 1998) also adopted this simplicity when using only the drag force in their models. Kafui et al. (2002) implemented a comprehensive derivation which considered the macro and micro variations of stresses.
\[ f_{fp_i} = \nabla \cdot \xi_f + f'_{fp_i} \]  
\[ \xi_f = -p\delta + \tau_f \]

where \( V_{pi} \) is the volume of particle \( i \); \( \xi_f \) is the total stress tensor of fluid; and \( f'_{fp_i} \) is the fluid force generated due to detailed variation of the point stress tensor of fluid around particle \( i \).

The total stress tensor can be written as

This indicates there are two components of stress tensor, the pressure and viscous (or deviator) stress, which leads to a pressure gradient and viscous fluid forces. Based on this analysis, Kafui et al. (2002) states that the total fluid force can include the drag and pressure gradient force, while unsteady forces for a gas-particle system can be ignored.

Of the potential fluid forces acting on particles under a flow, the drag force is the most significant component induced by fluid velocity. Several studies considered that the drag force consists of two parts induced by (i) fluid velocity and (ii) pressure gradient (Tsuji et al., 1993; Kawaguchi et al., 1998; Suzuki et al., 2007; Chen et al., 2011), whereas most other studies define the fluid velocity and pressure gradient forces separately (Xu and Yu, 1997; Kafui et al., 2002; Zeghal and El Shamy, 2008; Zhou et al., 2010; Shan and Zhao, 2014). The following literature review will focus on the drag force generated only from the fluid velocity.

One of the best models is based on the Ergun solution (Ergun and Orning, 1949), which was later improved by Wen and Yu (1966) for those porous media having \( n_f > 0.8 \). These works were then combined by Gidaspow’s research group (Gidaspow et al., 1992; Gidaspow, 1994), and is commonly called Gidaspow’s model; it is referred to in several early fluid-particle coupling studies (Tsuji et al., 1993; Kawaguchi et al., 1998; Suzuki et al., 2007; Chen et al., 2011). According to this method, the drag force is computed by
where \( \beta_d \) is the coefficient which is calculated according to the porosity, particularly:

\[
\beta_d = \begin{cases} 
\left( 1 - n_f \right) \left( \frac{150(1-n_f)\mu}{d_p n_f^2} + 1.75\rho_f n_f |U_p - U_f| \right) & (n_f \leq 0.8) \\
\frac{3}{4} C_d \frac{|U_p - U_f| \rho_f (1 - n_f)}{d_p} & (n_f > 0.8)
\end{cases}
\]

where \( d_p \) is the diameter of a particle, \( \mu \) is the dynamic viscosity of fluid; and \( C_d \) is the drag coefficient calculated by:

\[
C_d = \begin{cases} 
\frac{24(1 + 0.15Re^{0.687})}{Re} & (Re \leq 1000) \\
0.43 & (Re > 1000)
\end{cases}
\]

where \( Re \) is the particle Reynolds number. In this approach the coefficient \( \beta_d \) becomes the well-known Ergun equation (Ergun and Orning, 1949) when \( n_f \leq 0.8 \). The model shows a major role of the difference \( (U_p - U_f) \) in the magnitude of the drag force. Eventually, in those works by Zeghal and El Shamy (2004, 2008), only the original Ergun equation is used without considering different ranges of porosity.

Di Felice (1994) proposed a straightaway model which was then adopted in a wide range of modern studies (Xu and Yu, 1997; Kafui et al., 2002; Zhou et al., 2010; Shan and Zhao, 2014). In this method the drag force is given by

\[
f_d = 0.5C_d \rho_f \frac{\pi D_p^2}{4} n_f^2 (U_p - U_f) |U_p - U_f| n_f^{-(x+1)}
\]

where the drag coefficient is computed by

\[
C_d = \left[ 0.63 + \frac{4.8}{Re^{0.5}} \right]^2
\]

In this work a smooth development of drag force over variations in the fluid velocity and
porosity is obtained (Fig. 2.24).

Fig. 2.24 Compare different drag force models (Kafui et al., 2002)

The most preferable scheme of CFD-DEM coupling is that fluid cells are treated as macro compared to the micro behaviour of particles in DEM. This means the dimensions of the CFD cell must be larger than the particles so that the averaged fluid variables such as pressure and velocity in the cell can be used to calculate the interaction with particles. This meshing approach is also known as the coarse grid approximation method and the averaged Navier-Stokes equations are used instead of the original forms (Tsuji et al., 1993; O’Sullivan, 2011) (Fig. 2.25). A wide range of studies used various size ratios of fluid cell to particle diameter, i.e., from 1 to 5 (Chen et al., 2011; Smuts et al., 2012; Zhao and Shan, 2013; Shan and Zhao, 2014).
Although the CFD-DEM coupling concept was originally used to simulate a fluidised bed on the basis of the fluid mechanic perspective, a lot of effort has been made in recent years to use this technique to simulate geoengineering problems because multi-phases, such as fluid-solid media are very common in soil mechanics and geoengineering. Zeghal and El Shamy (2004, 2008) used the coupling to model liquefaction where the excess pore pressure rises up due to cyclic load and results in a severe deformation. In a microscopic consideration they showed the migration of soil particles due to an increasing drag force which resulted in a redistribution of porosity in this domain. This study has indicated that CFD-DEM coupling can capture the fluid-particle interaction in geomechanics very well.

Mittelbach and Pohl (2014) performed a coupled CFD-DEM simulation of rip-rap revetments. They used the clumping technique to simulate the polygonal shape of rip-rap stones while fluid flow was described by CCFD software; their results showed a reasonable agreement between the numerical behaviour of stones and experimental observation. Using the open source software LIGGGHTS and OpenFOAM, Shan and Zhao (2014) predicted the influence of debris flows and rock avalanches on the reservoir. Despite a lack of validation with experimental data, their study has shown a detailed analysis of the dynamic behaviour of...
water in a reservoir due to granular flow.

Fig. 2.26 Modelling rip-rap revetment under tidal flow (Mittelbach and Pohl, 2014)

While there are numerous geoengineering problems where multi-phases are considered, numerical modelling where the behaviour of the fluid and particles is considered in parallel has not been addressed properly. Although CFD-DEM coupling can well capture fluid-particle media, there are only few applications where this approach has been used to model geoengineering issues, particularly the interaction between fluid and geomaterials. This therefore requires an urgent study to look into this novel method and enable it to be more applicable in geoengineering.
Chapter 3 INFLUENCE OF BIODEGRADABLE NATURAL FIBRE DRAINS ON THE RADIAL CONSOLIDATION OF SOFT SOIL


3.1 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 (Rujikiatkamjorn et al., 2007); Changi Airport, Singapore (Chu et al., 2009); and Second Bangkok International Airport, Thailand (Indraratna et al., 2005d), 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 (Lee et al., 1994; Jang et al., 2001; Kim and Cho, 2008) 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.
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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 Venkatappa Rao et al. (2000). A typical prefabricated vertical jute drain includes 3 to 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 (Asasutjarit et al., 2007), 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. (2009), 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. (2009) pointed out that jute fibre degrades much faster in an acidic environment having a pH value less than 5.2. Saha et al. (2012) also found that the fibre can degrade rapidly in conditions of pH less than 4 or higher than 9. Particularly, he claimed that only about 10% to 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 (1995); and Fitzpatrick and Shand (2008). 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, 2008); and Saha et al. (2012).

Although several recent studies, such as those reported by Kim et al. (2011) and Deng et al. (2013) 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 (Jang et al., 2001). In addition, NPVDs usually have significantly lower initial discharge capacities (Jang et al., 2001; Asha and Mandal, 2012) 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 micro-biological studies have provided evidence of such exponential decay of natural materials attributed to biological attack (Means et al., 1985; Pronk et al., 1992; Harvey and Crundwell, 1997; Gamage and Asaeda, 2005; Manzoni et al., 2012). The predictions of the proposed analytical method were also compared with those obtained from a numerical approach.

3.2 Radial consolidation without drain degradation

3.2.1 Axisymmetric condition

With reference to Barron (1948), the governing equation for radial consolidation within a unit cell (Fig. 3.1a) can be written as:
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\[ c_h \left( \frac{1}{r} \frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial r^2} \right) = \frac{\partial u}{\partial t} \]  \hspace{1cm} [3.1]

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.

Fig. 3.1 Conversion from axisymmetric to plane strain unit cells

The solution for Eq. [3.1] can be represented as follows (modified after Hansbo (1981)):  
\[
\frac{u(t)}{u_o} = \exp \left( \frac{-8T_{h,a}}{\mu_a} \right) \] \hspace{1cm} [3.2]

where  
\[
T_{h,a} = \frac{c_{h,a} t}{d^2} \] \hspace{1cm} [3.3]
\[
\mu_a = \frac{n^2}{n^2 - 1}\left[\ln\left(\frac{n}{s}\right) + \frac{k_{h,a}}{k_{s,a}}\ln(s) - \frac{3}{4}\right] + \frac{s^2}{n^2 - 1}\left[1 - \frac{s^2}{4n^2}\right] \\
+ \frac{k_{h,a}}{k_{s,a}}\left(\frac{1}{n^2 - 1}\right)\left[\frac{s^4 - 1}{4n^2} - s^2 + 1\right] \\
+ \pi \frac{2k_{h,a}}{3d_w} l^2 \left(1 - \frac{1}{n^2}\right)
\]  

In the above, the subscript \(a\) indicates the axisymmetric condition, \(T_h\) is a dimensionless time factor for horizontal drainage, \(\overline{u(t)}\) is the average excess pore pressure at time \(t\) over the region of the unit cell, \(u_o\) is the uniform initial excess pore pressure, \(\mu_a\) is a parameter representing the well resistance \(q_w\), smear effect \((s=d_e/d_w)\) and influence zone \((n=d_e/d_w)\), where \(d_e\) and \(d_s\) are the diameters of the influence and smear zones, \(d_w\) is the equivalent diameter of the vertical drain, \(l\) is the length of the drain, and \(k_h\) and \(k_s\) are the horizontal permeability coefficients of the undisturbed and smear zones, respectively.

In the above solution, the parameters representing the drain characteristics can be grouped into two categories, namely the discharge capacity \(q_w\) and the geometric factors, including the equivalent diameter \(d_w\) and length \(l\). In the conventional approach, no degradation of the drain was considered, so these parameters were assumed to be constant over time.

3.2.2 Plane strain condition

Modelling soil in two-dimensions (2D) plays an important role in practical designs and it requires a procedure for converting parameters from axisymmetric to plane strain conditions. The equivalent unit cell problems for soil incorporating a PVD are illustrated in Fig. 3.1. The original idea of conversion for the radial consolidation of soil was introduced by Hird et al. (1992), and since then this method has been developed and applied in numerous studies such as those by Indraratna and Redana (2000); and Indraratna et al. (2005a). The
governing equation for the equivalent plane strain problem can be written as:

\[ c_h \frac{\partial^2 u}{\partial x^2} = \frac{\partial u}{\partial t} \]  \[ 3.5 \]

The solution for this equation can be written as follows (Indraratna and Redana, 2000):

\[ \frac{\bar{u}(t)}{u_o} = \exp \left( -\frac{8T_{h,p}}{\mu_p} \right) \]  \[ 3.6 \]

In the above, the subscript \( p \) refers to the plane strain condition where \( T_{p,a}, \mu_p \) are determined by:

\[ T_{h,p} = \frac{c_{h,p}t}{(2b_e)^2} \]  \[ 3.7 \]

\[ \mu_p = \left( \alpha + \frac{k_{h,p}}{k_{s,p}} \beta + \theta_w \right) \]  \[ 3.8 \]

where

\[ \alpha = \frac{2}{3} \frac{(n-s)^3}{n^2(n-1)} \]  \[ 3.9 \]

\[ \beta = \frac{2(s-1)}{n^2(n-1)} \left[ n(n-s-1) + \frac{1}{3}(s^2 + s + 1) \right] \]  \[ 3.10 \]

\[ \theta_w = \frac{4}{3} \frac{l^2}{b_e q_{w,p}} \]  \[ 3.11 \]

and where \( n = b_e/b_w \); \( s = b_s/b_w \); \( \alpha, \beta \) and \( \theta_w \) are the parameters accounting for the influence zone, the smear zone and the well resistance, respectively; \( b_e, b_s \) and \( b_w \) are the width of the influence zone, smear zone, and drain well, respectively (Fig. 3.1).

### 3.3 Analytical solution for radial consolidation with drain degradation

As Fig. 3.2 shows, natural fibres are generally expected to function fully as vertical
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drains until the soil consolidation reaches the design target. After serving as vertical drains, natural fibres should finally be converted to an organic component of the soil. The dissipation of excess pore pressure can be retarded significantly if the discharge capacity of the drain decreases sufficiently as a result of biodegradation. Because the current analytical method for radial consolidation is based on Barron’s (1948) concept and refers to conventional PVDs that are assumed to have constant drainage characteristics during consolidation, the negative impact of drain degradation on consolidation is ignored. Therefore, it is essential to establish a solution at the design stage that can estimate consolidation with respect to the drain degradation. The following sections will discuss the mathematical solution used to predict the dissipation of excess pore pressure while considering how drains actually decay.

Fig. 3.2 Degradation of NPVDs correlated with consolidation of soil

In this mathematical approach, the discharge capacity of a drain is assumed to decay uniformly along the depth over time, while the geometric parameters are considered to be constant. An experimental investigation conducted by (Kim and Cho, 2008) on the discharge capacity reduction of several natural fibre drains, including straw and jute fibre drains, installed in soft clay revealed that the drain degradation may initiate quickly after installation,
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whereby the rate of degradation is a function of the type of natural fibre and the environmental and/or chemical conditions of the soil. In this paper, the degradation of NPVD is assumed to initiate immediately after installation following an exponential decay function to represent its discharge capacity with time.

Moreover, the degradable discharge capacity of a NPVD should approach a certain limit value over time, because it is expected that natural fibres will be completely transformed into organic components of the soil. So at this stage the drain can be considered to be a column of organic matter and soil whose drainage characteristics are very difficult to determine. In this study, at the final state, the drain was assumed to have the same drainage characteristics as the soil in the smear zone.

In the proposed analytical approach, mathematical formulation was carried out for a unit cell containing a single drain based on both axisymmetric and plane strain conditions. A number of elemental assumptions were also made in respect to this study, including: (i) the soil was fully saturated and all the external vertical loads were initially borne by an increase excess pore pressure; (ii) the pore water was incompressible and laminar flow was considered in accordance with Darcy’s law; (iii) the equal strain concept was assumed (Barron, 1948); (iv) excess pore pressure dissipated radially causing only vertical deformation in the whole unit cell; and (v) small strain theory was adopted.
3.3.1 Axisymmetric condition

By considering flow through an elemental axisymmetric unit cell with radius \( r \) and height \( dz \) (Fig. 3.3) and assuming that the geometric parameters of the NPVD are constant over time, geometrically integrating the flow through the whole unit cell must lead to the same results as those obtained for the CPVD. As indicated by Indraratna et al. (2005a), the average excess pore pressure of the unit cell \( u \) can be written as:

\[
\bar{u} = \frac{\int_{0}^{l} \int_{r_w}^{r_s} u_s (2\pi r) dr dz + \int_{0}^{l} \int_{r_s}^{r_e} u_u (2\pi r) dr dz}{V} \tag{3.12}
\]

where \( u_s \) and \( u_u \) are the excess pore pressures in the smear and undisturbed zones, respectively; \( r_w, r_s \) and \( r_e \) are the radius of the drain well, and the smear and influence zones, respectively; \( V \) is the total volume of a unit cell with radius \( r_e \) and length \( l \), so that \( V = \pi(r_e^2 - r_w^2)l \).

It should be noted that both \( u_s \) and \( u_u \) are functions of both time \( t \) and position \( r \), while the average value \( \bar{u} \) is a function of time \( t \) only. Note that for convenience the superior bar, indicating an average value, has now been removed from the symbol \( u \) in Equation [12] and in the following formulation.
After integrating and re-arranging Eq. [3.12], the average excess pore pressure \( u(t) \) is given by:

\[
\begin{align*}
u &= \frac{\gamma_w}{2k_{h,a}} \frac{d^2}{4} \left( \mu_{n,s,a} + \mu_{q,a} \right) \frac{\partial \varepsilon}{\partial t} \\
\end{align*}
\]

[3.13]

In the above, \( \varepsilon \) is the vertical strain of the soil mass; \( \mu_{n,s,a} \) is a parameter that considers the effects of the smear and influence zones, \( \mu_{q,a} \) represents the effect of the discharge capacity reduction, and \( \gamma_w \) is the unit weight of the pore fluid. Because \( u \) and \( \varepsilon \) are functions of time only, Eq. [3.13] may be rewritten in terms of full rather than partial differentials, hence:

\[
\begin{align*}
u &= \frac{\gamma_w}{2k_{h,a}} \frac{d^2}{4} \left( \mu_{n,s,a} + \mu_{q,a} \right) \frac{d\varepsilon}{dt} \\
\end{align*}
\]

[3.14]

The determination of \( \mu_{n,s,a} \) and \( \mu_{q,a} \) can be represented as shown below.

\[
\begin{align*}
\mu_{n,s,a} &= \frac{n^2}{n^2 - 1} \left[ \ln \left( \frac{n}{s} \right) + \frac{k_{h,a}}{k_{s,a}} \ln(s) - \frac{3}{4} \right] + \frac{s^2}{n^2 - 1} \left[ 1 - \frac{s^2}{4n^2} \right] \\
&+ \frac{k_{h,a}}{k_{s,a}} \left( \frac{1}{n^2 - 1} \right) \left[ \frac{s^4 - 1}{4n^2} - s^2 + 1 \right] \\
\mu_{q,a} &= \frac{2}{3} \pi \frac{k_{h,a}}{q_{w,a}(t)} l^2 \left( 1 - \frac{1}{n^2} \right) \approx \frac{2}{3} \pi \frac{k_{h,a}}{q_{w,a}(t)} l^2 \\
\end{align*}
\]

[3.15]

[3.16]

In the above, \( q_{w,a}(t) \), which is a function that captures the decrease of the drain discharge capacity over time, is introduced and incorporated into Eq. [3.14] describing the dissipation of excess pore pressure.

The well-known relationship between the dissipation of excess pore pressure and the compressibility of soil can also be written as shown below:
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\[
\frac{d\varepsilon}{dt} = -m_v \frac{du}{dt}
\]  \(3.17\)

where \(m_v\) is the coefficient of volume compressibility for one-dimensional compression. By substituting Eq. \(3.17\) into Eq. \(3.14\) and re-arranging, the following expression can be obtained:

\[
u + \frac{\gamma_w m_v d_e^2}{2k_{h,a}} \left(\mu_{n,s,a} + \mu_{q,a}\right) \frac{du}{dt} = 0
\]  \(3.18\)

Eq. \(3.18\) is an ordinary differential equation with variable time \(t\) and it can be generalised as follows.

\[u + f(t) \frac{du}{dt} = 0\]  \(3.19\)

In the above, the general function \(f(t)\) is written as:

\[f(t) = \chi_a \left(\mu_{n,s,a} + \frac{\lambda_a}{q_{w,a}(t)}\right)\]  \(3.20\)

where

\[
\chi_a = \frac{\gamma_w m_v d_e^2}{8k_{h,a}} = \frac{d_e^2}{8c_{h,a}}
\]  \(3.21\)

\[
\lambda_a = \frac{2}{3}\pi k_{h,a} l^2
\]  \(3.22\)

The general solution for Eq. \(3.19\) yielding the average excess pore pressure \(u_a\) at time \(t\) with a given form of discharge capacity reduction \(q_{w,a}(t)\), can then be represented by:

\[u_a(t) = u_o \exp\left(-\int_0^t \frac{1}{f(t)} \, dt\right)
\]  \(3.23\)
3.3.2 Plane strain condition

For the same geometric information assumed for the plane strain CPVD system, the average excess pore pressure of a unit cell using a NPVD in plane strain condition is given by:

\[
\frac{b_e^2 \gamma_w m_v}{2k_{h,p}} \left[ \mu_{n,s,p} + \mu_{q,p} \right] \frac{du}{dt}
\]

In the above equation,

\[
\mu_{q,p} = \frac{4}{3} \frac{k_{h,p} l^2}{b_e} \frac{1}{q_{w,p}(t)}
\]

\[
\mu_{n,s,p} = \alpha + \frac{k_{h,p}}{k_{s,p}} \beta
\]

In the form of an ordinary differential equation, Eq. [3.24] can be generalised as follows:

\[
u + h(t) \frac{du}{dt} = 0
\]

The general function \( h(t) \) is given by:

\[
h(t) = \chi_p \left( \mu_{n,s,p} + \frac{\lambda_p}{q_{w,p}(t)} \right)
\]

where

\[
\chi_p = \frac{b_e^2 \gamma_w m_v}{2k_{h,p}} = \frac{b_e^2}{2c_{h,p}}
\]

\[
\lambda_p = \frac{4}{3} \frac{k_{h,p} l^2}{b_e}
\]

As with the analytical solution for axisymmetric conditions shown above, the general solution for Eq. [3.27] can be given by:
For the same conditions of load and soil, the dissipation of excess pore pressure over time in the axisymmetric and plane strain models should be the same. In other words, \( f(t) \) should be equal to \( h(t) \), and therefore, in conjunction with Eq. [3.20] and Eq. [3.28], the following relationship can then be obtained:

\[
\chi_a \left( \mu_{n,s,a} + \frac{\lambda_a}{q_{w,a}(t)} \right) = \chi_p \left[ \mu_{n,s,p} + \frac{\lambda_p}{q_{w,p}(t)} \right]
\]

Re-arranging the above yields:

\[
\left( \frac{k_{h,p}}{k_{h,a}} \right) = \left( \frac{b_e}{r_e} \right)^2 \left( \frac{\mu_{n,s,p} + \frac{\lambda_p}{q_{w,p}(t)}}{\mu_{n,s,a} + \frac{\lambda_a}{q_{w,a}(t)}} \right)
\]

where the ratio \( b_e/r_e \) represents the correlation of geometry between the axisymmetric and plane strain models. Setting a geometric scale factor \( f_g = b_e/r_e \) which enables the plane strain model to have different geometric features from the axisymmetric one, gives:

\[
\left( \frac{k_{h,p}}{k_{h,a}} \right) = \left( f_g \right)^2 \left( \frac{\mu_{n,s,p} + \frac{\lambda_p}{q_{w,p}(t)}}{\mu_{n,s,a} + \frac{\lambda_a}{q_{w,a}(t)}} \right)
\]

Matching the axisymmetric and plane strain systems as represented by Eq. [3.34] is a complex procedure that involves a number of unknown parameters in the plane strain model, namely the soil permeability \( k_{h,p} \); the geometric parameters \( f_g \), \( \mu_{n,s,p} \), \( \lambda_p \); and the discharge capacity of the drain \( q_{w,p} \). Eq. [3.34] can be satisfied by matching each group of parameters independently or simultaneously. Hird et al. (1992) demonstrated that independently matching the permeability and geometric parameters leads to almost identical results. For
simplicity, most previous studies (Indraratna and Redana, 1997, 2000; Indraratna et al., 2005a) considered the same geometric parameters in both systems, particularly \( r_e = b_e \) \((f_g = 1)\); \( r_s = b_s \) and \( r_w = b_w \). In fact, using a larger geometric scale for the plane strain model \((f_g > 1)\) can help to reduce errors in numerical computation due to a small drain spacing and very large numbers of finite elements.

To simultaneously match the axisymmetric and plane strain models, the condition represented in Eq. [3.34] can be mathematically re-arranged by the following set of relations:

\[
\begin{align*}
    k_{h,p} &= m (f_g)^2 k_{h,a} \quad [3.35] \\
    \mu_{n,s,p} &= m \mu_{n,s,a} \quad [3.36] \\
    \frac{\lambda_p}{q_{w,p}(t)} &= \frac{m \lambda_a}{q_{w,a}(t)} \quad [3.37]
\end{align*}
\]

where \( m \) is a matching factor.

From Eq. [3.36], the following relationship can be obtained:

\[
\frac{k_{h,p}}{k_{s,p}} = \frac{m \mu_{n,s,a} - \alpha}{\beta} \quad [3.38]
\]

The feature of a unit cell where \( k_{h,p} > k_{s,p} \) means that the ratio \( k_{h,p}/k_{s,p} \) should be greater than 1, and that leads to a requirement of \( m \) being greater than \((\alpha + \beta)/\mu_{n,s,a}\). Combined with Eq. [3.35], the minimum value of \( k_{s,p} \) can be identified when \( m \) approaches infinity, as shown below:

\[
\min(k_{s,p}) = \lim_{m \to +\infty} \left[ (f_g)^2 \left( \frac{m \beta}{m \mu_{n,s,a} - \alpha} \right) k_{h,a} \right] = (f_g)^2 \left( \frac{\beta}{\mu_{n,s,a}} \right) k_{h,a} \quad [3.39]
\]

Physically, \( k_{h,p} \) is the permeability of the undisturbed soil in the plane strain model so its value should be within the common range of values for the soil permeability. Mathematically, given a value of \( m > (\alpha + \beta)/\mu_{n,s,a} \) and replacing factors in Eq. [3.34], [3.35] and [3.36] with
reference to the parameters of the axisymmetric system, the parameters in a plane strain model, including the permeability \( k_{h,p} \), the geometry \( \mu_{n,s,p} \) and the discharge capacity \( q_{w,p} \), can be obtained.

By considering the influence zone in the axisymmetric and plane strain systems as being the same size \( (f_g = 1) \), Eq. [3.35] can be simplified as:

\[
k_{h,p} = mk_{h,a}
\]  \hspace{1cm} [3.40]

On the other hand, for a unit length of drain and assuming that the average flow over the cross section of a unit cell in each model is the same, the equality of the discharge capacity in both systems at time \( t \) is given by:

\[
q_{w,p}(t) = \left( \frac{2}{\pi R_a} \right) q_{w,a}(t)
\]  \hspace{1cm} [3.41]

With respect to Eq. [3.38], the above relationship allows Eq. [3.36] to be satisfied with any value for the matching factor \( m \), and therefore, a simultaneous matching procedure between the axisymmetric and plane strain models with respect to condition Eq. [3.38] and \( f_g = 1 \) can be simplified to Eq. [3.35] and Eq. [3.36] only. Moreover, without condition Eq. [3.37], the conversion method using the matching factor \( m \) is applicable for conventional radial consolidation without considering drain degradation. Note that the conversion technique discussed in this study can only be used to obtain the average excess pore pressure of the soil in a plane strain unit cell; the distribution of excess pore pressure within the cell has not been considered.

In previous studies (Indraratna and Redana, 1997, 2000; Indraratna et al., 2005a), the following relationship between \( k_{h,p} \) and \( k_{h,a} \) was commonly adopted:

\[
\frac{k_{h,p}}{k_{h,a}} = \frac{2 (n - 1)^2}{3 n^2} \frac{1}{(\ln(n) - 0.75)}
\]  \hspace{1cm} [3.42]
In this approach, the effects of smear and well resistance were ignored. In fact, using Eq. [3.42] yields a value of $m$ that is within the range of this factor mentioned above.

### 3.3.3 Application of the proposed analytical method for specific forms of $q_w(t)$

In order to verify the proposed analytical solution for radial consolidation considering reduced drain discharge capacity, a specific form of $q_w(t)$ must be given. A few biological studies (Pronk et al., 1992; Harvey and Crundwell, 1997) have shown the exponential growth of bacteria in ferrous and ferric medium (e.g., pyritic acidic sulphate soil in estuarine plains), while a number of mathematical models (Means et al., 1985; Gamage and Asaeda, 2005; Manzoni et al., 2012) predicting an exponential decay of organic matter (e.g., jute, straw) based on scientific evidence have also been established. In view of the above, in this study, the following exponential decay function for the discharge capacity was assumed in order to obtain an explicit analytical solution for consolidation.

$$q_w(t) = q_{wo} e^{-\omega t}$$  \[3.43\]

where $\omega$ is the decay coefficient that represents the rate of degradation of the drain discharge capacity; and $q_{wo}$ is the initial discharge capacity of the drain. Clearly $\omega$ should be within the range $[0, +\infty]$.

By respectively replacing function $f(t)$ in Eq. [3.20] by the decay functions [3.43] and integrating Eq. [3.23] yields:

$$u(t) = u_o \exp \left\{ \frac{-8T_{h,\alpha}}{\mu_{n,s,\alpha}} + \frac{1}{\chi_{\alpha} n_{s,\alpha}} \left[ \ln \left( \frac{\mu_{n,s,\alpha}}{\mu_{q,\alpha}} + e^{-\omega t} \right) - \ln \left( \frac{\mu_{n,s,\alpha}}{\mu_{q,\alpha}} + 1 \right) \right] \right\}$$  \[3.44\]

In the above, $\mu_{q,\alpha}$ is the value of the parameter $\mu_{q,\alpha}$ as determined by Eq. [3.16] with an initial discharge capacity $q_{wo,\alpha}$ of the drain in the axisymmetric model. Eq. [3.44] is the exact solution for describing the dissipation of excess pore pressure by a single drain under axisymmetric conditions with respect to the exponential form of the drain discharge capacity.
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This solution consist of two parts, where the first component $-8T_{h,a}/\mu_{n,s,a}$ represents the geometric characteristics of a unit cell, including the smear and influence zones, and where the second component considers the reduction of the discharge capacity. It is interesting that this equation approaches the conventional solution of Hansbo (1981) when the decay coefficients $\omega$ approaches zero (no degradation considered), that is:

$$\lim_{\omega \to 0} \left\{ \frac{1}{\chi_a \mu_{n,s,a}} \ln \left( \frac{\mu_{n,s,a}}{\mu_{q,o}} + e^{\omega t} \right) - \ln \left( \frac{\mu_{n,s,a}}{\mu_{q,o}} + 1 \right) \right\} = \frac{\mu_{q,o,a} t}{\chi_a \mu_{n,s,a} (\mu_{n,s,a} + \mu_{q,o,a})} \quad [3.45]$$

where $\mu_{n,s,a} + \mu_{q,o,a} = \mu_a$. Replacing Eq. [3.45] with Eq. [3.44] where $\omega \to 0$, and rearranging, results in the conventional solution shown in Eq. [3.2], which does not consider the degradation of the drain. In other words, when the decrease of drain discharge capacity is insignificant and can be omitted, the conventional solution becomes valid.

By following a process similar to that presented above, the exact solution for the radial consolidation of soil by a single NPVD under plane strain condition, in conjunction with the exponential reduction of drain discharge capacity, is given by:

$$\frac{u(t)}{u_o} = \exp \left\{ -\frac{8T_{h,p}}{\mu_{n,s,p}} \right\} + \frac{1}{\chi_p \mu_{n,s,p}} \omega \left[ \ln \left( \frac{\mu_{n,s,p}}{\mu_{q,o,p}} + e^{\omega t} \right) - \ln \left( \frac{\mu_{n,s,p}}{\mu_{q,o,p}} + 1 \right) \right] \quad [3.46]$$

where $\mu_{q,o,p}$ is the value of $\mu_{q,p}$ as determined by Eq. [3.25] with an initial discharge capacity $q_{w0,p}$ of a drain in the plane strain system.

### 3.4 Numerical model for radial consolidation incorporating degradation of NPVDs

Numerical modelling of conventional (polymeric) vertical drains based on the finite
element method (FEM) without any consideration of degradation has been conducted successfully in the past as reported in several studies (Hird et al., 1992; Indraratna and Redana, 2000; Indraratna et al., 2005a). In this study, the finite element technique as implemented in the ABAQUS code (version 6.12) was used to simulate the radial consolidation of a unit cell by a NPVD incorporating the decay of drain discharge capacity.

Fig. 3.4 Finite element discretization of soil in a unit cell: a) geometric characteristics of model; and b) the fundamental element for plane strain and axisymmetric analyses

An assumption of soft soil properties was made in these analyses. The permeability of soil in the undisturbed zone was $1.0 \times 10^{-9}$ m/s and the ratio $k_{h,d}/k_{s,a}$ of 3.0 was used. An elastic model was adopted to describe the deformation of soil with $m_v = 5 \times 10^{-2}$ m$^2$/kN and $\nu = 0$ indicating that no lateral displacement was allowed, as required for one-dimensional
deformation. The consolidation analysis in ABAQUS was implemented based on Biot theory (Hibbitt et al., 2012). A surcharge pressure of 50 kPa was placed on top of the unit cell, and this pressure was assumed to be borne completely by the pore water in the cell during the initial stages. The rate of consolidation was evaluated by considering the dissipation of excess pore pressure \( u(t)/u_o \). The top, bottom, and side boundaries of the cell were set as impermeable (Fig. 3.4a); and only flow through the drain well of the unit cell was allowed.

The sizes of natural fibrous drains vary, but they are generally larger than polymeric PVDs which normally have an equivalent diameter \( d_w \) of 50 mm. Prefabricated vertical jute drains (PVJD) are normally 80-110 mm wide and 6-12 mm thick. In this study, the equivalent diameter of the NPVD = 70 mm was used with respect to the approximation \( d_w = 2(a_w + b_w)/\pi \) where \( a_w \) and \( b_w \) are the thickness and width of the drain. Despite jute drains being much thicker than polymeric PVDs, many trials and field practices have shown that jute drains can be installed very effectively with a conventional mandrel so the smear zone, which is mainly influenced by drain installation process, should be the same in both unit cells using PVJD and CPVD. According to Indraratna and Redana (1998), the ratio of the diameter of the smear zone to the drain well \( (d_s/d_w) \) is about 3 to 4. In this paper, the ratio \( d_s/d_w \) of 3.4 was assumed. For the geometric factor \( f_g = 1 \), a unit cell with \( d_e = 0.6 \) m, \( d_s = 0.24 \) m and \( l = 20 \) m was created (Fig. 3.4a). 8-noded bi-quadratic displacement and bi-linear pore pressure elements (CPE8P and CAX8P) were assigned for the plane strain and axisymmetric analyses, respectively.

In order to simulate the reduced drain discharge capacity, a subroutine that captures the degradation of a drain was established and coupled with ABAQUS. An equivalent degradation function of the drain permeability \( k_w(t) \) was formed on the basis of the degradation function of the discharge capacity \( q_w(t) \). By updating the value of the drain permeability in every time step, which is governed by the function \( k_w(t) \) in the external
subroutine of the finite element analysis, the effect of drain degradation on the dissipation of the excess pore pressure could be estimated.

3.5 Modelling results and discussion

In the following applications of the analytical method, the soil properties and drain characteristics were the same as those described in the numerical approach discussed above. A prefabricated vertical jute drain (PVJD) was considered as the NPVD in this study.

3.5.1 Radial consolidation by NPVD without drain degradation

![Graph showing consolidation rates](image)

Fig. 3.5 Conventional solution without drain degradation considering different size of CPVDs and NPVDs.

For the same size unit cell and soil characteristics, the consolidation rate predicted for the NPVD was slightly higher than that of the CPVD (Fig. 3.5). As discussed in previous sections, natural fibre drains have a larger equivalent diameter than CPVDs, although the smear effect for these drains was considered the same as the CPVDs because the same steel mandrel can be used to install both types of drains. This resulted in a slight difference in excess pore pressure dissipation between the two cases, according to the conventional

\[k_h = 1.0 \times 10^{-9} \text{ m/s}\]
\[\frac{k_h}{k_s} = 3\]
\[c_h = 0.63 \text{ m}^2/\text{year}\]
\[d_e = 0.6 \text{ m}; s = 3.4; l = 20\text{ m}\]
analysis (i.e., without evaluating drain degradation).

Fig. 3.6 Results of converting axisymmetric to plane strain models using different matching factor $m$, without degradation of drain: a) finite element method; b) analytical method.

Fig. 3.6 shows the results of converting the axisymmetric to plane strain conditions with reference to a varying value of the matching factor $m$ (Eq. [3.35] and [3.36]) without considering drain degradation. The analytical conversion using Eq. [3.2] and [3.6] showed almost perfect agreement between the axisymmetric and plane strain models for a given value of $m$, while the numerical approach showed slight deviations when considering the results of plane strain conversions for different magnitudes of $m$. The lowest bound of $m$ (0.15, according to Eq. [3.38] and the condition $k_{h,p}/k_{s,p} = 1$) indicated the highest value of $k_{s,p}$ and the smallest value of $k_{h,p}$ that caused a swift dissipation of excess pore pressure at the early stage, but a slower progress toward the end of consolidation. Increasing the value of $m$ ($k_{h,p}/k_{h,a}$) enabled the undisturbed zone to attain a higher permeability, but caused the
permeability of the smear zone to gradually approach its limit value (9.2x10^{-11} m/s, according to Eq. [3.39]). Since the permeability of the smear zone varied within a narrow range as the matching factor \( m \) changed from 0.15 to infinity, the shift in the dissipation curve of excess pore pressure was insignificant. The curve corresponding to the conventional value of the matching factor (\( m = 0.5 \) according to Eq. [3.42]) was shown as the best fit.

### 3.5.2 Analytical solution for radial consolidation including drain degradation

Considering the exponential reduction of drain discharge capacity with the decay coefficient \( \omega = 0.015 \text{ day}^{-1} \), the proposed analytical method retarded the dissipation of excess pore pressure significantly compared to the conventional method without drain degradation (Fig. 3.7). For the period that the discharge capacity of the drain was very large (initially 40 days), its degradation did not hamper the dissipation of excess pore pressure very much, and no clear difference between the two curves on Fig. 3.7 could be observed. After 40 days, when the discharge capacity of the drain was below 0.25 m³/day, the dissipation of excess pore pressure by the degradable drain deviated clearly from the conventional solution. Moreover, the proposed analytical method showed that the dissipation of excess pore pressure had become seriously impeded after 300 days, while the conventional solution could not capture this trend because it did not consider any drain degradation. Fig. 3.7 also shows that after 400 days the predicted consolidation curve for the degrading drain was almost horizontal over time (critical state of decay) at a residual ratio \( u(t)/u_o \) around 20% with a very small dissipation rate of excess pore pressure. This is because the drain had reached an extremely low discharge capacity. Note that by using \( \omega = 0.015 \text{ day}^{-1} \), the discharge capacity of the drain decreased to 1.0x10^{-3} m³/s (equivalent to the permeability of the drain 3.2x10^{-6} m/s) after 400 days.
Fig. 3.7 Analytical solution for radial consolidation considering drain degradation: a) exponential reduction of discharge capacity; b) Consolidation rate with and without consideration of drain degradation

Fig. 3.8 represents the radial consolidation of a degradable drain subjected to different levels of degradation. A range of decay coefficients from 0.01 to 0.03 day\(^{-1}\) which are consistent to laboratory test results obtained for PVJD installed in acidic soft clay due to the oxidation of pyrite were considered. For the most serious case (\(\omega = 0.03\) day\(^{-1}\)) where the discharge capacity of the drain reduced to \(1.0 \times 10^{-3}\) m\(^3\)/s in 200 days, the consolidation rate started to decrease significantly after almost 80 days, and then reached a critical state of decay after only 200 days. In the less severe cases of degradation where \(\omega = 0.02\) and 0.01 day\(^{-1}\), the consolidation curves turned into a critical state of decay after 300 days and 500 days respectively. This critical state of decay indicated a period where the permeability of the drain became very small and resulted in a very slow rate of excess pore pressure dissipation.

Note that the characteristics of the degradation curve and the final state (the limit value of the discharge capacity) of degradation were the major factors determining how severely the
dissipation of excess pore pressure can be retarded. In this study, the permeability of the drain was assumed to decrease continuously to a limit value of $3.3 \times 10^{-10}$ m/s in accordance with the exponential function of discharge capacity and the various decay coefficient $\omega$.

![Analytical method considering different rate of degradation: a) different rates of drain degradation; b) dissipation of excess pore pressure](image)

Additionally, the results indicated that the obstruction of excess pore pressure dissipation only became apparent when the discharge capacity reduced to a small level that was obviously dependent on soil properties such as the consolidation coefficient $c_h$; and the geometry of the unit cell (i.e., $d_e$ and $l$). In this study, the value of the drain discharge capacity that began to retard the soil consolidation significantly was approximately $0.1 \text{ m}^3/\text{day}$.

3.5.3 Comparison between analytical and numerical approaches

The numerical simulation for radial consolidation using a degradable drain in an axisymmetric condition indicated good agreement with the results obtained from the
analytical method (Fig. 3.9). For the same soil properties and degradability of drain \( (\omega = 0.02 \text{ day}^{-1}) \), the FEM and analytical methods showed almost the same excess pore pressure response, with only about 4% maximum difference during the whole period of consolidation. Unlike the analytical method, the FEM indicated a slightly lower dissipation rate at the initial stage and then a gradual reversal after 80 days. At the critical state of decay, the dissipation curve predicted by the FEM was insignificantly lower than that predicted by the analytical method. This result demonstrates that the proposed analytical solution can accurately describe radial consolidation with respect to the degradation of a drain.

Fig. 3.9 Results of finite element and analytical methods for axisymmetric condition with drain degradation.

The predictions of the FEM for the case of radial consolidation by the degradable drain under plane strain condition using the matching factor technique for the conversion of properties were compared to those obtained by the FEM for axisymmetric condition. Fig. 3.10a shows excellent agreement between the dissipation of excess pore pressure in the axisymmetric and plane strain conditions predicted by the analytical approach, but as shown in Fig. 3.10b, there were slight deviations in the results obtained from the FEM. For different values of \( m \) from 0.15 to 100, the discharge of excess pore pressure captured by the FEM for
plane strain conditions is consistent with the outcome from the FEM assuming axisymmetric condition. Any deviations between these curves did not exceed 4% during the whole period of consolidation. This result indicates that the matching factor technique can accurately convert the axisymmetric condition to a plane strain condition for radial consolidation by the biodegradable drain.

Fig. 3.10 Results of models for radial consolidation using the degradable drain in plane strain condition ($\omega = 0.02$ day$^{-1}$): a) by analytical method; b) by FEM

3.5.4 Comparison with previous studies

In this section, the proposed analytical solution is compared to the results of previous studies including: (i) experimental work conducted in the laboratory by Kim et al. (2011) to evaluate the effect of the decreasing discharge capacity of a vertical drain in a unit cell on soil consolidation; and (ii) the analytical method proposed by Deng et al. (2013). A unit cell with $d_e = 0.6$ m; $d_s = 0.3$ m; $d_w = 0.05$ m and $l = 2$ m was used for calculation with reference to the
laboratory work of Kim et al. (2011). In this work, a drain was installed into a bock cell which contains a soft soil collected from the field. The initial discharge capacity of the drain \( q_{\infty} = 0.014 \, \text{m}^3/\text{day} \) was measured by Kim et al. (2011) and a decay coefficient \( \omega = 0.259 \, \text{day}^{-1} \) was obtained by Deng et al. (2013) when using an exponential curve to fit the measured data of Kim et al. (2011) (Fig. 3.11a). Note that the normalised data shown in Fig. 3.11a is made based on the given raw measurement by Kim et al. (2011). The soil parameters, including \( k_h = 3.6 \times 10^{-10} \, \text{m/s}; \) \( c_h = 3.154 \, \text{m}^2/\text{year} \) and the ratio \( k_h/k_s = 1.05 \) were also adopted according to Deng et al. (2013).

![Graph showing the comparison between the proposed analytical method and other studies.](image)

**Fig. 3.11** Comparison between the proposed analytical method and other studies: a) reduction curves of discharge capacity; b) dissipation of excess pore pressure

The results shown in Fig. 3.11b indicated good agreement between the current analytical method and the data measured in the laboratory by Kim et al. (2011). The analytical curve remained approximately 5% higher during the first 7 days and then gradually approached the experimental trend until it was slightly lower at the end of the investigation.
This behaviour could be explained by the deviation of the drain discharge capacity between the measured and fitted curves, as shown in Fig. 3.11a. Because the exponential equation with $\omega = 0.259$ day$^{-1}$ could not capture accurately the sharp drop in the discharge capacity in the first days of the experiment, a gap between the analytical and experimental results can be seen in Fig. 3.11b. When the exponential curve was closer to the measured one, the dissipation of excess pore pressure was simulated more accurately by the proposed analytical method. An improvement of the degradation function $q_w(t)$, which can describes more accurately the measured data, would lead to a better prediction. The proposed formulation is able to incorporate such degradation functions.

In comparison to the analytical solution of Deng et al. (2013), the results showed almost the same behaviour of excess pore pressure with respect to the exponential reduction of discharge capacity. A slight deviation between the two methods can be seen in Fig. 3.11 because Deng et al. (2013) solved the governing equation for the average excess pore pressure by an approximate approach whose accuracy depended on the number of iterations, while an exact solution was proposed and applied in this study. Both analytical solutions were based on the same concept of Hansbo (1981) and considered the reduction in discharge capacity. While Deng et al. (2013) assumed that an additional excess pore pressure was generated in the drain due to the decrease of discharge capacity and integrated the exponential degradation function of drain permeability, the current solution introduced a general form of drain discharge capacity and incorporated it into the governing equation for excess pore pressure dissipation. In this way, a more flexible solution that could accommodate various forms of the reduction of drain discharge capacity was obtained. Note that in this study, only exponential degradation was considered. However, Eq. [3.23] and [3.31] could be applied to any given form of degradation or a combination of several forms at a time.
3.6 Conclusions

In this study, an analytical solution that can describe the consolidation behaviour of soil with respect to the degradation of natural fibre drains was proposed, in view of scientific evidence available from past microbiological studies. A time-dependent reduction of the drain discharge capacity was incorporated into the theory of soil consolidation, and in order to obtain an explicit mathematical solution, an exponential form of reduction for the drain discharge capacity was adopted. The following conclusions could be drawn:

3.6.1 The proposed analytical solution can capture the effect that drain degradation has on the radial consolidation of soil. Compared to the conventional method that does not include drain degradation, the dissipation of excess pore pressure can be retarded significantly when drain degradation is included. A higher value of the decay coefficient $\omega$ leads to a serious obstruction of soil consolidation.

3.6.2 The results obtained by the FEM with a subroutine capturing the behaviour of the degrading drain also agreed well with the results based on the analytical method. The difference between the results of these two approaches was less than 4% and that indicated an acceptable degree of accuracy of the approximate analytical solution.

3.6.3 The matching technique used to convert the parameters from axisymmetric to plane strain conditions showed the flexibility of the method in obtaining a wide range of parameters for plane strain condition. Given any matching factor $m > (\alpha + \beta)/\mu_{n,s,a}$, the variation of consolidation curves was insignificant. The method was successfully applied to both cases of radial consolidation with and without drain degradation.

3.6.4 The results obtained from the proposed solution also agreed well with the laboratory measurements with reference to the reduced discharge capacity. The deviation between the analytical and experimental methods was less than 5% during the whole period of the investigation.
Apart from the salient findings summarised above, the modelling attempts, including the analytical and numerical approaches, provided a better insight into the practical implications of soil consolidation as affected by drain degradation. In the absence of reliable data, an exponential decay function for discharge capacity was adopted in this study, but that may not be the most accurate mathematical form. A better understanding of the rate of degradation of natural fibre in a specific geochemical environment may improve the proposed model for given ground conditions, particularly when field data becomes available in the future.

3.7 Acknowledgements

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Chapter 4 LABORATORY INVESTIGATION INTO

BIODEGRADATION OF JUTE DRAINS WITH

IMPLICATIONS FOR FIELD BEHAVIOUR

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4.1 Introduction

Soil improvement using natural prefabricated vertical drains (NPVDs) (also known as natural fibre drains) has been carried out in several regions, especially in South and Southeast Asia, ever since the first NPVD was introduced by Lee et al. (1987). Many field observations (Lee et al., 1994; Lee et al., 2003; Kim and Cho, 2008) have shown that NPVDs with favourable engineering characteristics such as excellent discharge capacity and resistance to deformation, i.e., bending and kinking are a viable alternative to synthetic prefabricated vertical drains (SPVDs) made from polymeric materials, which are seen as possibly having an adverse effect on the natural environment (Gregory and Andrady, 2003). However, many of these applications were in inert soils, which may not harm the engineering properties of the drains, so their biodegradation characteristics have not received any serious attention. Under adverse environments such as bioactive soils, in which cellulose degrading microorganisms exist, the decay process of cellulose-based materials such as jute is very serious; for example, Miura et al. (1995) show a severe degradation of a jute fibre drain buried in Ariake clay where the drain lost almost 78% of its tensile strength after only 126 days. Because saturated soft soils, especially alluvial soils which normally have a large organic content and complex...
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biological profiles, are the areas where NPVDs are most likely to be considered for ground improvement, there is an urgent need to evaluate the biodegradation of drains in those conditions.

While raw natural fibres such as jute and coir can be used to make NPVDs which are normally band-shaped with a number of coir cores wrapped by layers of jute geotextiles (Fig. 4.1a), the straw which is a sub-product of rice fields and very popular in Asian countries is used to create circular drains, as Kim and Cho (2008) describe. This study shows that straw fibre drains have a lower discharge capacity than jute fibre drains but they can still discharge excess pore pressure at an acceptable rate. Jute and coir are the most commonly used materials to manufacture drains because they have distinct engineering characteristics such as durability and high hydraulic conductivity, and are also abundant in many developing countries where the demand for ground improvement is often high. Jute has more than 80% cellulose and only around 12% lignin (Som et al., 2009), making the fibre less durable than coir which has approximately 40% lignin and 43% cellulose (Gupta, 2011). Those chemical features also indicate that the biodegradation of jute depends primarily on the decomposition of cellulose, while lignin plays a key role in the decomposition of coir.

There are a number of key factors affecting the decomposition of organic matter such as jute and straw, these include: (i) the chemical properties of the material; which means the more lignin, the more durable the fibre, and (ii) environmental conditions such as temperature, humidity, chemical components and activities of microorganisms. A pilot project by (Kim and Cho, 2008) reports a much faster decomposition of NPVDs in warmer seasons where microorganisms are more active due to the higher temperature. Laboratory investigations (Som et al., 2009; Saha et al., 2012) indicate a large impact of the acidity in the environment on the biodegradation of jute fibre. However, these studies consider the influence of the chemical (e.g., acidity), physical (e.g., humidity and temperature), and
biological (e.g., bacteria) factors on the fibre degradation independently, whereas natural fibres used to improve soft soil are usually subjected to those factors simultaneously, so the degradation of drains in the field is more complicated. While the biodegradation of naturally occurring materials is an unavoidable issue when using them in practice, there is a lack of studies addressing the mechanism of biodegradation that natural fibres such as jute and coir undergo in saturated soft soil. It is therefore important to clarify how the biodegradation can occur in those media and under which conditions caution in the field is needed.

Indraratna et al. (2016) have evaluated the effect that the biodegradation of NPVDs can have on the consolidation of soil by considering an exponential reduction in the discharge capacity of drains. This study indicates that the dissipation of excess pore pressure can be severely retarded due to biodegradation in the drain, and also indicates there is a need to exercise caution when installing NPVDs in adverse soils. The current study seeks to further clarify the mechanism of drain biodegradation through a laboratory investigation, where prefabricated vertical jute drains (PVJDs) are buried in saturated soft clays. The reduction in the tensile strength of this fibre is recorded over time and there is an intensive biological analysis using the genomic sequencing technique to identify microbes which consume the natural fibres. The results are then used to improve the analytical method to predict soil consolidation proposed by Indraratna et al. (2016).

4.2 Laboratory investigation into the biodegradation of NPVDs

This section presents the findings of a laboratory investigation into the biodegradation of natural fibre drains buried in different types of saturated soft clay obtained from the field. Of the existing NPVDs, prefabricated vertical jute drains (PVJDs) are the most commonly used, as many previous studies indicate (Lee et al., 1994; Lee et al., 2003; Kim and Cho, 2008; Asha and Mandal, 2015). A typical PVJD, which is usually 8 to 12 mm thick and 100 to 120 mm wide, includes 4 to 5 coconut cores wrapped by 1 to 2 layers of jute sheath (Fig.
4.1a) to make the filter layer. Jute and coir bundles making the drain are created from individual fibres which are extracted from jute plants and coconut husks (Rahman, 2010; Gupta, 2011). Common jute geotextiles which are used as the filter have an apparent opening size (AOS) that varies from 150 to 400 μm which is much larger than the size of clay particles. In this structural format, jute fibre plays a major role in the discharge capacity of the drains.

![Diagram of prefabricated vertical jute drain](image)

a) Structure of prefabricated vertical jute drain

![PVJD sample inserted into soft clay](image)

b) Drain insertion

![pH measurement](image)

c) pH measurement

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Fig. 4.1 PVJD sample inserted into soft clay and pH measurement
4.2.1 Experimental scheme

Clay soil was collected from 1.5 to 1.8 m deep layers at the National Soft Soil Field Testing Facility (NFTF) at Ballina, Australia. The water content of these natural soils varied from 57 to 65 % and there was a neutral acidic level (pH from 6.2 to 7.2). Their organic content varied from 3.5 to 4.2 % which was slightly larger than those measured in Ballina clay by Pineda et al. (2016). The salinity of pore water extracted from natural soil was approximately 16 g/l, as revealed by an electrical conductivity measurement. Pineda et al. (2016) show there is a small concentration of ion (i.e., Fe$^{2+}$ and Mg$^{2+}$ with less than 1.0 g/l) and a larger amount of sodium (1-2.5 g/l) and chloride (2-4 g/l) in the 1.5-2 m deep soil at Ballina.

This soil was then reconstituted using neutral water and commercial vinegar (acetic acid) with a pH of 2.9 to create different environmental conditions. The acidity was managed with a portable pH meter (Spectrum Technologies Int, 2011). Three cases were generated with the following details:

(i) Soil/Container 1: Natural soil mixed with neutral water with a pH of 6.8 to create a sample having a pH of approximately 6.4 and a water content of 90.6%.

(ii) Soil/Container 2: Natural soil mixed with vinegar and neutral water to form a reconstituted medium having an average pH of 4.8 and water content of 91.3%.

(iii) Soil/Container 3: Natural soil mixed with vinegar to form a medium with an average pH of 3.5 and a water content of 93.8%.

The oxidation reduction (or redox) potential test that is widely used to measure the propensity of a solution to contribute or accept electrons was carried out on the above media over time. The index obtained from these tests indicates the concentration of oxidants (e.g., oxygen, manganese, iron, sulphate) and reductants which play an important role in many reactions of biological systems (Delaune and Reddy, 2005). A more negative redox potential
represents a lower concentration of oxidants and a more anaerobic condition of soil where its microbial characteristics will change over the biochemical reaction which regulates the metabolism of microorganisms in the medium. This parameter was measured with a meter using a platinum tip probe (TPS, 2012).

A number of PVJD samples were buried in the above soil samples (Fig. 4.1b), and their containers were kept in a conditioned dark room at 22°C and 88% relative humidity. This ensured that physical parameters such as temperature, light, and humidity remained constant over time and the same in every sample. After specific periods of time, i.e., 15, 30, 60, 120, 180, 240, 300, 520 and 630 days, the samples were removed and then subjected to tension tests to determine whether or not they had degraded. The acidity (pH) and ORP of the media were noted respectively.

4.2.2 Tension tests on fibre drains

The degradation of fibres drains was evaluated by recording the decreasing tensile strength of the fibres over time. These tension tests were carried out on the completed drain and individual fibres (coir and jute) extracted from the drain (Fig. 4.2). The diameter of single fibres was determined by microscope and their tensile strength was calculated by referring to the applied tension force and corresponding cross-sectional area; in this process, degradation in the tensile strength of single fibres was obtained. Since the coir fibres were sufficiently large, the tensile strength can be measured by testing individual fibres whereas with the jute fibres, this parameter was obtained via a tension test on bundles of fibres. The average tensile strength of jute fibre was then estimated on the basis of the tension force of the whole bundle and the total cross-sectional area of individual fibres in the bundle.

In this investigation, the equivalent diameter of jute fibre varied from 12 to 78 \( \mu m \) while coir fibre was much larger and its diameter varies from 109 to 512 \( \mu m \). The aspect ratio (the ratio of length to diameter) of jute and coir fibres varied approximately from 350 to 8000.
and 200 to 1600, respectively. Note that physical properties of jute fibres which are composed of ultimate cells having the size from 0.7 to 6 mm in length and 10 to 25 µm in diameter (Gupta, 2011) are strongly influenced by manufacture processes, i.e., retting and extraction. For each stage of tensile strength testing, tests were carried out on 20 samples to ensure the reported result was accurate and representative. The initial tensile strength of fibres was assumed to be identical because all the samples of fibre drains studied in this investigation were extracted from the same manufactured package. The average tensile strength of fresh jute and coir in this study was 480 ± 38 MPa and 172 ± 27 MPa, respectively, which corroborate values reported in previous studies (Defoirdt et al., 2010; Gupta, 2011).

![Tension test on fibre drains](image)

**Fig. 4.2 Tension test on: (a) the whole drain; and (b) individual fibres**

### 4.2.3 Discharge capacity test on fibre drains

To determine how the discharge capacity of fibre drains had changed over time and different soil conditions, a discharge capacity test which was established with reference to the
testing model used in previous studies (Jang et al., 2001) was carried out on the drains

Fig. 4.3 Discharge capacity test: a) schematic view; b) drain extracted from soil and wrapped by membrane; and c) drain being confined by cell pressure.
extracted (Fig. 4.3a). In this investigation, the drain was wrapped by a membrane and placed vertically in a cell in which the confining pressure applied on the drain was managed via cell pressure (Fig. 4.3b and c). The inlet water was generated by a constant head tank while the discharge volume at the outlet was recorded over time. The hydraulic gradient was controlled by the difference in water heads between the inlet and outlet. Manometers with an accuracy of 1 mm were used to measure water heads at the inlet and outlet of the drain. The discharge capacity of drain was calculated on the basis of the hydraulic gradient and discharge volume at the outlet of the drain with respect to ASTM D4716 (2008).

Note that in this investigation, a layer of soil remained on drains after extracting from containers was kept during confining. By this approach, the influence of soil, e.g., clogging on hydraulic conductivity of fibre drains was included. The hydraulic gradient was generated from 0.1 to 0.5 which was close to field condition as suggested by Chu et al. (2004). The confining pressure including 10, 50 and 100 kPa was applied in this study.

4.2.4 Microbial analysis of degraded natural fibres

To obtain an insight into the biodegradation of a fibre drain, an uncultured approach known as DNA sequencing was applied to microorganisms in the samples (Fig. 4.4). Biomolecular techniques have been used extensively over recent decades to identify microorganism in soil, as seen in studies by Kirk et al. (2004), Liu et al. (2006) and Maron et al. (2011). In this study, the Illumina sequencing technique was used. This Next Generation Sequencing (NGS) technique has been developed intensively and applied widely in recent years to profile the microbial community due to its low cost and time efficiency (Barba et al., 2014).
Figs. 4.4 DNA analysis for decayed fibres: a) fibres extracted from saturated soil; b) fibres in DNA extraction process.

Fibres with surrounding soil particles were extracted from the containers (Fig. 4.4a) and then maintained in freezing conditions because the microbial characteristics can be preserved well at freezing temperatures, as Rubin et al. (2013) show. The extraction and purification of DNA were carried out with a Powersoil DNA Isolation kit in accordance with its manufacture’s protocol (MO BIO Laboratories Inc, 2016); this technique has proved its efficiency for many soils (Mahmoudi et al., 2011). The raw DNA extracted was then subjected to the Polymerase Chain Reaction (PCR) technique to specify and amplify the DNA (Singh et al., 2014), and the DNA read and analysis were further processed. Microbial profiles were then obtained by assigning the sequence data to the Greengenes database (DeSantis et al., 2006). By this approach the identification and characterisation of the microorganisms responsible for the biodegradation of the natural fibres (i.e., jute and coir) were clarified. Note that this microbial data presents population of different microbes over different samples however it does not quantitatively link to mechanical behaviours such as the discharge capacity of drains and consolidation of soil in this study.

4.2.5 Discussion of experimental results

Tensile strength of fibre drains

The decreasing tensile strength of jute fibre subjected to different soft soil conditions
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is shown in Fig. 4.5a; these results came from samples extracted from the different containers, but at the same depth (i.e., 40 cm). Jute buried in soil 1 decayed faster than samples exposed to soils 2 and 3. After approximately 70 days, variations in the tensile strength of jute were almost the same in every case, and are insignificant, but the degradation curves clearly deviated after this period. Soil 1 had the fastest reduction, with the average tensile strength of jute decreasing from 480 MPa to 315 MPa and 73 MPa after 150 days and 300 days, respectively; in particular the fibre lost almost 90% of its initial tensile strength after 500 days. This reduction in the tensile strength of jute is much less severe in soils 2 and 3, and while the jute in soil 2 maintains approximately 48% of its initial strength after 520 days, almost 80% of the tensile strength of the fibre buried in soil 3 remains after the same time period.

![Graph showing tensile strength of jute in different soils](image)

a) Individual jute and coir fibres       b) Complete drains

Fig. 4.5 Reduction in tensile strength: a) individual fibres: b) complete drains

The results of a tension test on fibres located 5 cm deep in soil 1 are shown as the dashed curve in Fig. 4.5a; note that these fibres degrade much more than those deeper down in the same container. The tensile strength of fibre in the surface soil decreases to almost 25 MPa after about 300 days and 100% of its original value disappears after around 500 days. This indicates there is a considerable deviation in the rate and amount of biodegradation at different depths in the same soil. These results also show that the degradation of jute only
becomes apparent after around 70 days in saturated soil.

Unlike the severe degradation of jute described above, coir does not decay very much (Fig. 4.5a). In fact it retains more than 80% its original tensile strength after nearly 600 days and there is no significant deviation in the degradation curves of fibres exposed to different saturated soils, which indicates that coir resists biodegradation far better than jute.

Fig. 4.5b shows the reduction in tensile strength of the whole drain, which included both jute and coir bundles; in the first nearly 70 days the decrease in tensile strength is insignificant but then it becomes quite significant, particularly in soil 1 where the environment had a more neutral acidity. The tensile strength of the drain exposed to soils 2 and 3 from 70 to 630 days decreases gradually at different rates, i.e., 2.3 N/day and 0.86 N/day, respectively, whereas the tensile strength of the drain in soil 1 reduces steeply to approximately 1 kN after 300 days and then gradually slows down. This occurs because the jute fibres had decayed so much when losing nearly 85% their initial tensile strength (Fig. 4.5a), thus making the overall strength rely mainly on the strength of the coconut cores which could still resist biodegradation, even after 300 days. By way of comparison, Miura et al. (1995) have shown how jute drains installed in Ariake clay lost 78% of their initial tensile strength after only 120 days.

*Discharge capacity of fibre drains*

The recorded discharge capacity of drains over time and different confining pressures is presented in Fig. 4.6. It is commonly agreed that the higher the confining pressure, the lower the discharge capacity. For example, in fresh condition (0 day) in which drains were not contaminated by soil, the discharge capacity of drains decreases from 0.45 to 0.27 and 0.21 m$^3$/day as the confining pressure changes from 10 to 50 and 100 kPa, respectively. Note that a slight reduction in discharge capacity occurs as time increases from 0 to 15 days because soil was not included in those tests at fresh (0 day) condition. These results
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corroborate with previous studies (Jang et al., 2001; Kim and Cho, 2008; Asha and Mandal, 2012) which reported the discharge capacity of natural fibre drains (e.g., jute, coconut and straw fibre drains) varies from 0.39 to 3.0 m$^3$/day over different drains and discharge capacity tests. These values are relatively smaller than those of conventional synthetic PVDs which normally have the discharge capacity from 1.2 to 9.5 m$^3$/day under the same confinement as reported in previous studies (Jang et al., 2001; Asha and Mandal, 2012).

![Discharge capacity test results](image)

**Fig. 4.6 Discharge capacity test results** a) variation in discharge capacity with time and confining pressure; b) drain broken after extracting from soil after 520 days.
The reduction in discharge capacity of drains buried in soil 2 and 3 is not significant as Fig. 4.6a shows particularly at low confining pressure, i.e., 10 kPa. Although the reduction in discharge capacity of drains in soil 1 is more apparent at 10 kPa confining pressure, it is still not considerable with approximately 80% (i.e., 0.31 m$^3$/day) its initial capacity remained after 520 days. As the confining pressure increases to 50 and 100 kPa, the discharge capacity of drains buried in different soils begins to deviate apparently. While the discharge capacity of drains in soil 3 still decreases insignificantly at 50 and 100 kPa, it reduces more apparently in soil 2 particularly after 300 days. Soil 1 which resulted in severe reduction in tensile strength of jute fibres shows a much more significant reduction in discharge capacity of drains. At 50 kPa, the discharge capacity of drains in soil 1 begins to drop clearly from 0.22 m$^3$/day at 180 days to 0.021 m$^3$/day at 520 days. As the confining pressure increases to 100 kPa, the discharge capacity of drains in soil 1 even falls to a smaller level at 520 days, i.e., 0.009 m$^3$/day.

The variation curve in discharge capacity of drains (Fig. 4.6a) includes a certain period (intact period) in which the reduction in discharge capacity is insignificant over time followed by a decreasing period of discharge capacity. This study reports an intact period from 100 to 150 days in soil 1 but note that this can vary with different environmental (e.g., soil and temperature) and loading (confinement) conditions. The decreasing period is complex with a combination of concave and convex curves however it seems to reach a certain stable level after a severe reduction.

The above results indicate that the influence of different soil conditions on the discharge capacity of drains becomes more apparent as a larger confining pressure, i.e., 50 and 100 kPa is applied. This was because fibres having more degradation were less resistant to confinement, resulting in a more severe destruction in porous system of the drains. The larger the confining pressure, the more fibres were compressed and rearranged, leading to the
smaller porosity. Ash and Mandal (2012) investigate how different porous structures of NPVDs affect their discharge capacity and concluded that the stiffer the drain structure, the more the resistance to confinement and the larger the discharge capacity. As fibres decayed, their mechanical properties, i.e., the tensile strength reduced, making the fibre drains harder to maintain their porosity under confinement. Note that the discharge capacity test could not be completed on drains in soil 1 after 520 days because they were too weak and almost broken after extracting from soil (Fig. 4.6b).

Further observation on jute fibres under a microscope after 520 days (Fig. 4.7) indicated there are apparent differences between these decayed fibres exposed to different environments such that the more they decay, the denser they become; in fact fibres that decay due to the microorganisms metabolising tend to generate a dark compound (biomass) around the fibres, which reduces the porosity of the drain. After being washed, the fibres that experienced the worst damage to their structure were in soil 1, while the fibres exposed to soil 3 still retain the twisting structure which plays an important role in the hydraulic conductivity of fibre drains (Nguyen and Indraratna, 2017a, b). This indicates the considerable destruction that biodegradation can have on the microstructure of natural fibre drains, which can lead to the reduction in discharge capacity of drains as shown above.
Fig. 4.7 Degradation of jute under micro-observation
Fig. 4.8 shows how different the surfaces of the soils appear after 520 days. Soil 3 does not show very much biodegradation of fibres over the period under investigation, and its surface still looks fresh without any significant contaminants, whereas the surfaces of soils 1 and 2 are covered with a layer of yellow and brown compounds, as a result of different outcomes from bioactivities in those media.

![Image of soil surfaces](image)

a) Soil/container 1  
b) Soil/container 2  
c) Soil/container 3

Fig. 4.8 The surface of soils after 520 days: a) soil 1; b) soil 2; and soil 3

*Microbial characteristics of decayed fibres*

Because microbial characteristics are closely related to biochemical reactions in the medium as discussed above, variations of acidity (pH) and Oxidation Reduction Potential (ORP) over time are shown in Fig. 4.9. It is interesting that pH in all soils gradually increases, particularly in the period from 60 to 300 days. The neutralising medium stemming
from bacterial metabolism and incorporating the redox reaction has also been clarified in previous studies (Inglett et al., 2005; Muyzer and Stams, 2008). The ORP measured at the bottom of the container decreases quickly from around +30 mV in the first 30 days to a stable value of approximately -120 mV in the next 120 days. There is a much higher ORP at the surface layer with a stable value of around +60 mV, which indicates there is a higher concentration of oxidants in this position.

![Graphs showing pH and ORP variations over time](image)

**Fig. 4.9 pH and ORP variations over time**

The profiles of microorganisms in 3 media at phylum level (a genomic analysis after 630 days at 40 cm depth) are shown in Fig. 4.10, which indicates almost the same phylum-levelled bacteria but with different contributions to the media. Note that these bacteria (e.g., the phyla Firmincute and Proteobacteria) are generally the most dominant microbes found in soil (Fierer et al., 2007; Berg et al., 2012). The phylum Firmincute which contains almost Gram-positive bacteria (Goodfellow et al., 2009) is the largest component in soil 1 with around 38% of the total microbial population, however the contribution these bacteria make to the medium decreases in soil 2 and 3 with 25% and 13%, respectively. In contrast, the Proteobacteria predominate in soil 3 with 48.2% but are less significant in soils 2 and 1 with 36.4% and 26.4%, respectively. The phylum Fibrobacteria accounts for a significant
contribution (i.e., 17.6%) in soil 3, but it decreases to 10.8% and 5% in soil 2 and 1, respectively. It is also interesting to see an overwhelming role of the Firmicutes at the surface layer (i.e., 98% at 5 cm depth) of soil 1 where the degradation was the most severe. The difference these major bacteria make in the media can explain the deviation in the biodegradation process of natural fibre drains buried in such soils.

![Bacterial profile at phylum level of soils](image)

Fig. 4.10 Bacterial profile at phylum level of soils

Other minor bacteria such as Bacteroidetes, Actinobacteria, Chloroflexi exist in all 3 media with less than 10% for each. Bacteria with a contribution of less than 5% are grouped into the “Others” division, as shown in the figure. Note that bacteria account for almost 99% of the microbial community, as identified via the genomic analysis carried out in this study.

The variation of major bacteria at phylum level at different values of pH is shown in Fig. 4.11, where acidity in the medium makes a large contribution to the microbial properties. The Firmicutes increases rapidly from around 12% at a pH of 4.1 to nearly 40% at a pH of 7.2 whereas the Proteobacteria and Fibrobacteres decrease by approximately 20% when the medium becomes more neutral. There is also a slightly larger contribution made by Chloroflexi and Bacteroidetes when the pH increases to the neutral point. The driving role of
acidity in the structure of the microbial community is also discussed in previous studies by Lauber et al. (2009) and Rousk et al. (2010).

To further clarify how the biodegradation varied when fibre drains were installed into different saturated soils, an analysis at a deeper phylogenetic classification is essential because bacteria at phylum level are variable in their characteristics. Note that in the following discussion, because of the complexity in the microbial community, only major bacteria at family and genus levels obtained from the genomic analysis are addressed with respect to their bio-mechanism in decomposing organic matters. The detail of bacterial community found on jute fibres buried in different saturated soils is given in Appendix A.

The family Ruminococaceae is the predominant member of the phylum Firmicutes found in soil 1 at 40 cm depth (Appendix A, Fig. A1); these bacteria form the largest part (i.e., 29%) of the whole medium 1 but they are much less significant in soils 2 and 3 with approximately 12.6% and 5.2%, respectively. These anaerobic bacteria are able to ferment carbon sources such as glucose and acetate for their energy. Some species such as Acetivibrio cellulolyticus, Acetivibrio cellulosolvens and Ruminococcus flavefaciens can rapidly
decompose cellulose in a neutral environment (Patel et al., 1980; Goodfellow et al., 2009). The predominance of these bacteria in decayed fibre buried in soil 1 indicates how quickly they cause jute fibres to degenerate, as shown in the previous section, but when the medium becomes more acidic (i.e., soil 2 and 3), their population decreases and the decay process of jute fibre is not as serious.

There is an obvious difference of bacterial members making the phylum Firmicutes at the 5 cm depth of soil 1 (Fig. A2); this community includes only the class Bacilli (57.31%) and Clostridia (40.69%) in which the genus Bacillus and the Clostridium account for more than 40% of their population, respectively. Previous studies (Leschine, 1995; Trivedi et al., 2011) show that these bacteria can secrete the cellulase enzyme to ferment and break down the cellulose structure into basic unit glucose. Rahman (2010) in his review over the biodegradation of jute during retting also pointed out the major contribution of these bacteria to the degradation. Many species of the Clostridium such as Papyrosolvens, Lentocellum and Cellobioparum are commonly found in estuarine sediments and soil (Leschine, 1995).

The class Beta-, Gama- and Delta-Proteobacteria, which are members of the phylum Proteobacteria, are also major contributors to the media. Particularly the Deltaproteobacteria share about 23.8%, 27.2% and 19.4 % of the whole medium 1, 2 and 3, respectively while the Beta- and Gama-proteobacteria also occupy 12.4% and 9.8%, respectively of the microbial community in soil 3. Most families of these anaerobic bacteria such as Desulfobulbaceae making 66.8% of the Deltaproteobacteria in soil 1, Desulfarculaceae and Desulfovibrionaceae accounting for 32.2% and 46.7%, respectively of the Deltaproteobacteria in soil 2 can utilise sulphate, sulphur, or other oxidised sulphur compounds as electron acceptors for their metabolism (Barton and Hamilton, 2007; Muyzer and Stams, 2008). The prevalence of those microbes in the soils is understandable because alluvial and marine soils such as Ballina clay are normally rich in the oxidised sulphur
compounds which are vital for their metabolism (Barton and Hamilton, 2007; Muyzer and Stams, 2008) while the sulphate reducing bacteria are able to grow in soils with a large range of acidity, i.e., from extremely low pH of 2 to a pH of 10 (Muyzer and Stams, 2008).

The existence of the aerobic bacteria Bacillus, which require oxygen for their consumption of organic matter, indicates a higher concentration of oxygen in the surface layer of saturated soil, which in fact agrees with the ORP test (Fig. 4.9b). As well as those bacteria, the Ruminococcaceae is also considerable with 8.1% but still much less than their concentration at deeper layers. The predominance of the cellulose degrading bacteria in the surface soils discussed above clarifies why jute, with more than 80% cellulose, decayed much faster near the surface than samples buried deeper in the soil.

Although there was a large component of bacteria such as the sulphate reducing groups (i.e., the Deltaproteobacteria) which can decompose the organic compounds in soils 2 and 3, the jute fibres in these soils did not decay very much. This was because these bacteria are usually able to consume monomers such as glucose, acetate, organic acid (Barton and Hamilton, 2007; Muyzer and Stams, 2008), whereas cellulose (the major component of natural fibres such as jute) is a macromolecule (polysaccharide) which is composed of the basic unit glucose (Leschine, 1995). Cellulose and other carbohydrates need fermenting and breaking into monomers by particular microorganisms such as many species of the Ruminococcaceae, Clostridium and Bacillus before they can be consumed by other microbes such as sulphate reducing bacteria (Leschine, 1995; Muyzer and Stams, 2008). In soils 2 and 3, there was a paucity of microbes that can secrete enzymes to decompose cellulose into the fundamental substrates (i.e., glucose), so that even though there was a large amount of bacteria, such as sulphate reducing bacteria which can consume organic matter, jute in these soils did not decay much.

Coir has a large amount of lignin, i.e., 40% (Gupta, 2011) which is a highly complex
heteropolymer that makes the fibre highly resistant to biodegradation compared to carbohydrates such as cellulose and hemicellulose. In this fibre, lignin is bonded tightly with hemicellulose and cellulose fibrils to create a stiff composite (Jayabal et al., 2012). There is a significant limitation of current studies addressing lignin degrading bacteria, as reviewed by Bugg et al. (2011) and Brown and Change (2014). Most degradations of lignin observed in previous studies are induced by the ligninolytic enzyme activities of fungi, whereas only a few soil bacteria (i.e., Actinomycetes) can decompose this complex component (Kirby, 2005; Fernandes et al., 2011; Brown and Chang, 2014). Moreover, the degradation of lignin by bacteria is found much less effective than degradation by fungi (Dashtban et al., 2010; Brown and Chang, 2014), which usually require a high concentration of oxygen (Cookson, 1995; Inglett et al., 2005; Kato et al., 2015). This explains why the coir buried in saturated soils where the supply of oxygen is limited, had a very low rate of degradation.

4.3 Influence of biodegradation on soil consolidation

Vertical drains are normally expected to discharge excess pore pressure until the design target of consolidation is achieved (Fig. 4.12) as usually assumed in conventional approaches (Barron, 1948; Hansbo, 1981; Indraratna et al., 2005c; Rujikiatkamjorn and Indraratna, 2007), but the biodegradation of a natural prefabricated vertical drain (NPVD) can be very serious when exposed to an adverse environment where cellulose-degrading bacteria live, as shown above. This rapid degradation of natural fibres (i.e., jute) deteriorates the porous structure of drains (Fig. 4.7) and reduces the resistance of drains to confining pressure, which can then lead to a reduction in discharge capacity of drains. With respect to the results obtained through the laboratory investigation carried out in this study and previous works (Miura et al., 1995; Kim and Cho, 2008) which also report serious degradation of NPVDs, the influence of drain biodegradation is apparent and needs an urgent evaluation.
4.3.1 Evaluating the influence of drain biodegradation on soil consolidation

In a preliminary study without any experimental data, Indraratna et al. (2016) considered the effect of drain degradation on the consolidation of soil by incorporating the time-dependent function of drain discharge capacity \( q_w(t) \) into the dissipation of excess pore pressure. According to this approach, the general solution describing the radial consolidation of a unit cell with respect to the biodegradation of the drain is given by:

\[
\frac{u(t)}{u_0} = \exp \left( - \int_0^t \frac{1}{f(t)} \, dt \right) \tag{4.1}
\]

In the above, \( u_0 \) is the initial excess pore pressure, and \( f(t) \) is written as:

\[
f(t) = \chi \left( \mu_{n,s} + \frac{\lambda}{q_w(t)} \right) \tag{4.2}
\]

where \( \mu_{n,s} \) is the parameter representing the effect of geometry (i.e., the size of smear and influence zones), and is estimated as follows:
In the above $n = r_e/r_w$; $s = r_s/r_w$ where $r_e$, $r_s$ and $r_w$ are the radius of the influence, smear and well zones, respectively; $k_h$ and $k_s$ are the coefficients of permeability in the undisturbed and smear zones, respectively; $\lambda = (2\pi k_h l^2)/3$; $\chi = d_e^2/(8c_h)$ where $c_h$ is the consolidation coefficient for horizontal drainage; $l$ is the length of drain, and $d_e$ is the equivalent diameter of the drain.

Note that in this solution, as well as the fundamental study by Barron (1948) for the radial consolidation of soil, the following important assumptions are also included: (i) the geometric parameters (i.e., equivalent diameter and length) of the drain is constant while its discharge capacity decreases over time; (ii) degradation is uniform over the depth of installation; and (iii) the reduced discharge capacity reaches a limit level at which the jute fibres are completely absorbed into the organic components of the soil.

To obtain an exact solution for Eq. [4.1], a specific form of the degradation function $q_w(t)$ is needed. Indraratna et al. (2016), with reference to biological studies where the environmental conditions are different from those of saturated soil, assumed that the reduction of drain discharge capacity due to its biodegradation commences immediately after the NPVDs are installed into the soil, in accordance with an exponential degradation of the drain discharge capacity, as follows:

$$q_w(t) = q_{wo}e^{-\omega t}$$

where $\omega$ is the decay coefficient and $q_{wo}$ is the initial discharge capacity of the drain. Substituting Eq. [4.4] in Eq. [4.1] and integrating yield:
The above expression is the exact solution for the radial consolidation of soil assuming a mere exponential degradation of the drain discharge capacity. However, the decrease in the discharge capacity of the drain in the field can be more complicated due to the following reasons:

\[ \frac{u(t)}{u_o} = \exp \left[ \frac{-8T_{h,a}}{\mu_{n,s,a}} + \frac{1}{\chi_a \mu_{n,s,a} \omega} \ln \left( \frac{\mu_{n,s,a} + e^{\omega t}}{\mu_{q,o,a} + 1} \right) \right] \]  

\[ \text{[4.5]} \]

The above expression is the exact solution for the radial consolidation of soil assuming a mere exponential degradation of the drain discharge capacity. However, the decrease in the discharge capacity of the drain in the field can be more complicated due to the following reasons:

\( a \) Natural fibres do not usually decay immediately after drains are installed into soil, as shown in the laboratory investigation of this study, particularly in anaerobic conditions, because bacteria take time to colonise and consume organic matter (Inglett et al., 2005). This intact or inactive period can vary with different environmental conditions such as acidity and/or temperature.

\( b \) The degradation of a drain is not uniform over the depth of installation because the soil properties and temperature vary with depth, so in the upper layers of soil where the temperature and concentration of oxygen are higher, organic matter (i.e., jute and straw) can decay earlier and faster (as shown in this laboratory investigation). This can thus reduce the discharge capacity of the whole drain due to a combination of various degradation behaviours over the depth (Fig. 4.11).

\( c \) In addition to biodegradation which relies basically on the activity of microorganisms such as bacteria and fungi, the discharge capacity can also decrease due to clogging and deformation (bending and kinking). Several studies (Banerjee, 2012) have shown that although bending and kinking are not a serious problem with NPVDs, they can reduce the discharge capacity by approximately 10-15% when large settlement occurs. Moreover, because an NPVD is actually a combination of individual fibres in a certain arrangement, and the hydraulic conductivity of a fibre drain depends mainly
on its porosity (Nguyen and Indraratna, 2016, 2017b), clogging where soil particles and biomass build up due to the metabolism of microorganisms (see Fig. 4.7a) decreases the porosity of a fibre drain thus reducing its discharge capacity. Note that NPVDs such as PVJDs usually have much larger apparent opening size (AOS) of the filter (Fig. 4.1a) in comparison with the size of clay particles.

Considering the above field conditions (a, b and c), the simplified analytical solution originally proposed by Indraratna et al. (2016) which only consider exponential reduction in discharge capacity of drains needs to be significantly extended. The results from discharge capacity testing in the current study show a complex reduction behaviour (Fig. 4.6a) which is composed of different degradation forms over time. Therefore, in lieu of the exponential form of Eq. [4.4], a general polynomial degradation form that includes convex, concave and linear degradation curves, is considered as follows:

\[
q_w(t) = q_{wo}(1 - at^b) \tag{4.6}
\]

where \(a\) is the decay coefficient that represents the rate of degradation of the drain discharge capacity; and \(b\) is the order of the polynomial degradation curve. Clearly \(a\) and \(b\) should satisfy the condition: \(0 < (1 - at^b) < 1\). When \(b < 1\), the form of degradation becomes a convex function, while a concave curve emerges when \(b > 1\), and \(b = 1\) represents the linear reduction of discharge capacity over time. Note that the mathematical extension presented in this paper is based on the approach proposed by Indraratna et al. (2016) with respect to following assumptions: (i) the discharge capacity of drains degrades over time while other parameters, i.e., the diameter and length of drains are relatively unchanged; (ii) natural fibres finally turn into organic components of soil, and this biodegradation combined with other factors, i.e., deformation and clogging in the field results in a time-dependent reduction in discharge capacity of drains.
Replacing Eq. [4.6] into Eq. [4.1] and re-arranging yield:

\[
\frac{u(t)}{u_o} = \exp \left\{ - \int_0^t \frac{dt}{\frac{\chi}{\mu_{n,s} + \frac{\chi}{q_{wo}(1 - at^b)}}} \right\}
\]

Several specific values of \(a\) and \(b\) are considered, as follows:

(i) Convex form: \(b = 0.5; q_w(t) = q_{wo}(1 - a\sqrt{t})\)

\[
\frac{u(t)}{u_o} = \exp \left\{ \frac{-8T_h}{\mu_{n,s}} - \frac{2\mu_{qo}}{\chi a\mu_{n,s}^2} \left( \sqrt{t} + \frac{\mu}{a\mu_{n,s}} \ln(1 - \frac{\mu_{n,s}a\sqrt{t}}{\mu}) \right) \right\}
\]

(ii) Concave form: \(b = 2; q_w(t) = q_{wo}(1 - at^2)\)

\[
\frac{u(t)}{u_o} = \exp \left\{ \frac{-8T_h}{\mu_{n,s}} \right. \\
+ \frac{\mu_{qo}}{2\chi \mu_{n,s} \sqrt{\mu_{n,s} a}} \left[ \ln(\sqrt{\mu} + \sqrt{\mu_{n,s} a t}) - \ln(\sqrt{\mu} - \sqrt{\mu_{n,s} a t}) \right] \right\}
\]

(iii) Linear form: \(b = 1; q_w(t) = q_{wo}(1 - at)\)

\[
\frac{u(t)}{u_o} = \exp \left\{ \frac{-8T_h}{\mu_{n,s}} - \ln \left( 1 - \frac{\mu_{n,s} a q_{wo} t}{\mu_{n,s} q_{wo} t + \lambda} \right) \left( \frac{\lambda}{\chi \mu_{n,s}^2 a q_{wo}} \right) \right\}
\]

In the above, \(T_h\) is the time factor for horizontal drainage. \(\mu = \mu_{qo} + \mu_{n,s}\) where \(\mu_{qo} = (2\pi k_h l^2)/(3q_{wo})\) represents the discharge capacity of the drain at its initial stage. By providing these solutions for different orders of polynomial degradation curves, the complex behaviour associated with the reasons \(a\) and \(c\) as discussed earlier can then be captured in the revised model.

It is interesting to note that when \(a\) approaches zero (no degradation of the drain), the solutions presented above all approach the conventional solution proposed by Hansbo (1981).
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For example with linear degradation $b = 1$:

$$\lim_{a \to 0} \left\{ \ln \left( 1 - \frac{\mu_{n,s} a q_{w_0} t}{(\mu_{n,s} q_{w_0} + \lambda)} \right) \left( \frac{\lambda}{\chi \mu_{n,s}^2 a q_{w_0}} \right) \right\} = \frac{\mu_{q_0} t}{\chi \mu_{n,s} (\mu_{n,s} + \mu_{q_0})}$$ \[4.11\]

Replacing Eq. [4.11] into Eq. [4.10] and re-arranging the result in Hansbo’s solution, that is:

$$\frac{u(t)}{u_o} = \exp \left( \frac{-8T_h}{\mu} \right)$$ \[4.12\]

The consolidation of soil, including different forms of drain degradation, is given by accumulating the dissipation of excess pore pressure over $n$ individual stages corresponding to varying forms of $q_{w_i}(t)$, as follows:

$$u(t) = -\sum_{i=1}^{n} u_{0i} \exp \int_{t_{i0}}^{t_{ij}} \frac{1}{f_i(t)} \, dt$$ \[4.13\]

where $f_i(t)$ is the function $f(t)$ shown in Eq. [4.2] in stage $i$, where the reduction of the discharge capacity is described by the function $q_{w_i}(t)$ from $t_{i0}$ to $t_{ij}$. $u_{0i}$ is the initial excess pore pressure of stage $i$. For different forms of $q_{w_i}(t)$, i.e., the polynomial or exponential curves, corresponding solutions to capture the dissipation of excess pore water pressure are used. Clearly the total investigated time $t = \sum_{i=1}^{n} (t_{ij} - t_{i0})$. By this approach, the complex degradation characteristics of jute drains as pointed out earlier (i.e. reasons $a$, $b$ and $c$) can be incorporated in the time-dependent soil consolidation.

4.3.2 Prediction of soil consolidation considering various forms of degradation

In this section, because of the absence of sufficient field data, specific values of the soil parameters and degradation properties of drains are assumed to demonstrate the proposed solution for predicting the consolidation of soil. The consolidation coefficient is assumed to be 0.004 m$^2$/year. Because previous practices indicate that NPVDs can be installed by the conventional method using the same mandrel, the smear effect of NPVDs can be evaluated
by referring to previous studies (Indraratna and Redana, 1998) of conventional synthetic PVDs. The ratio $d_s/d_w$ of 3.4 is used in this paper, and the space ($S$) and length ($l$) of the drains are 0.85 m and 20 m, respectively. The horizontal permeability coefficient of $9 \times 10^{-10}$ m/s is adopted. An initial discharge capacity of 0.43 m$^3$/day was obtained by carrying out a discharge capacity test on a non-degraded PVJD.

Fig. 4.13 Different degradation forms of $q_w(t)$: a) discharge capacity; and b) corresponding dissipation of excess pore pressure.

Predictions made assuming the same final (zero) discharge capacity of the drains but with different forms of the degradation curve, viz., exponential, convex ($b = 0.5$), concave ($b = 2$), and linear ($b = 1$) reductions, as well as the conventional approach assuming constant discharge, $q_w$, are shown in Fig. 4.13a. While the exponential and convex degradations show a rapid reduction at the beginning and become slower at the end of the investigation, the
concave curve represents the opposite trend, responding slowly in the first days and then increasing in the later stages.

When the discharge capacity of the drains is subjected to different forms of degradation, the pore pressure dissipation and soil consolidation varies accordingly, as shown in Fig. 4.13b. The exponential degradation ($\omega = 0.008 \text{ day}^{-1}$) of the discharge capacity is the most serious case, and it causes the earliest retardation and the highest residual excess pore pressure (approximately 23%) after 500 days. Although the polynomial degradation with $b = 0.5$ begins to decrease at about the same rate initially as the exponential one, it slows significantly after the first 100 days, leading to a less severe retardation of the pore pressure dissipation curve. The concave reduction of the discharge capacity ($b = 2$), which is almost insignificant for the first 150 days, gradually accelerates towards the end of the investigation period and results in the least severe obstruction of excess pore pressure dissipation. The linear ($b = 1$) degradation represents a slightly bigger retardation of excess pore pressure than the quadratic reduction ($b = 2$) but it is still smaller than the exponential degradation. Compared to the case of constant discharge capacity, the dissipation of excess pore pressure is generally retarded, as expected, for all cases that assume a decrease in the drain discharge capacity with time. For example, with an exponential degradation, i.e., the case with the most severe reduction of discharge capacity at the beginning of the period under investigation, the dissipation of $u$ after 500 days is about 10% less than the case assuming a constant $q_w$ curve.

One application of the solution obtained by combining various forms of drain degradation over time is shown in Fig. 4.14. In this investigation (Fig. 4.14a), different reduction behaviours of the discharge capacity are assumed in addition to the conventional approach (constant $q_w$), as follows:

\begin{enumerate}
\item An exponential degradation with $\omega = 0.008 \text{ day}^{-1}$ occurs immediately after the drain is installed (no delay time).
\end{enumerate}
An initial delay (intact) period of 70 days where \( q_w \) remains constant is followed by an exponential degradation with \( \omega = 0.0089 \) day\(^{-1} \) for the rest of the investigation period.

An initial delay period of 20 days is followed by a concave polynomial \( (a = 2 \times 10^{-5} \) day\(^{-2} \) and \( b = 2) \) and this is followed by an exponential degradation with \( \omega = 0.00913 \) day\(^{-1} \). Compared to case (c.2), a transition period of 80 days (with polynomial degradation) is added.

Fig. 4.14 Dissipation of excess pore pressure considering different degradation forms of discharge capacity over time: a) combined different forms of degradation; b) corresponding dissipation of excess pore pressure.

Note that these degradation curves all reach the same final level of drain discharge capacity. Although the discharge capacity test in this study has shown an intact period from 100 to 150 days, Kim and Cho (2008) presents an earlier start of the reduction through their
laboratory test, indicating a complex reduction behaviour in discharge capacity of natural fibre drains. This section hence assumes an intact period less than 100 days to demonstrate how the analytical model can capture the corresponding soil behaviour. Case (c.1) represents a single form of degradation (exponential) while cases (c.2) and (c.3) show a combination of multiple forms of $q_w$ degradation over time, which is probably more realistic. The consolidation of the soil in case (c.1) is predicted by Eq. [4.5] for the purely exponential degradation of the drain, whereas for the multi-form degradation, Eq. [4.13], incorporating solutions for conventional, polynomial ($b = 2$) and exponential degradation, is used.

Fig. 4.14b shows how the consolidation induced by a single form differs from one induced by a multiple-form of degradation. Case (c.1) has the earliest degradation that results in the highest residual excess pore pressure after 500 days while the combined reduction forms, i.e., cases (c.2) and (c.3), which have $q_w$ decreasing after an initial delay stage, do not obstruct the dissipation of excess pore pressure very much. Case (c.2) having the initial 70 days without any degradation, followed by an exponential reduction, has the consolidation curve retarded slightly more severely than case (c.3) where the intact period of the drain is shorter (i.e., 20 days) but the rate of degradation in the exponential reduction stage is higher ($\omega = 0.00913$ day$^{-1}$).

4.3.3 Model Limitations

Although the analytical model proposed in this paper has shown a certain success in capturing the influence of drain degradation on soil consolidation, it has not been validated properly with consolidation data particularly in the field. Because this is an evolving area in bio-geomechanical research where there is a significant lack of understanding, more studies addressing this area particularly in the field is essential.
4.4 Conclusions

A laboratory investigation where samples of Prefabricated Vertical Jute Drain were installed in saturated soft soil with different levels of acidity was carried out. In this study, the degradation of the tensile strength of jute and coir was recorded over time and a genetic analysis of the decayed fibres was implemented to identify the microbial properties of the medium. Based on these laboratory results, an analytical method to predict the consolidation behaviour of soil incorporating the biodegradation of natural fibre drains was proposed, and the following conclusions can be drawn.

4.4.1 Coir retained more than 80% of its original tensile strength after more than 600 days exposed to saturated soil, indicating an outstanding resistance to biodegradation, exceeding the performance of jute which lost around 85% its fresh strength after 300 days buried in neutral conditions. No particular lignin degrading microorganisms were found in all soils investigated. Lignin is a major component of coir.

4.4.2 Discharge capacity of fibre drains buried in soil 1 did not decrease significantly at low confining pressure however it begun to decrease considerably as the confining pressure increased. After 300 days exposed in soil 1, the discharge capacity of drains reduced from 0.26 and 0.19 m$^3$/day to 0.05 and 0.025 m$^3$/day under 50 and 100 kPa confining pressure, respectively. Drains buried in soil 2 and 3 did not show considerable reduction in discharge capacity over the period of experimentation.

4.4.3 The biodegradation of jute was significantly influenced by the acidity of the medium. Soil with a neutral condition resulted in the fastest decay of jute while a more acidic medium (i.e., pH of 3.5 to 4.5 in soils 2 and 3, respectively) made biodegradation less severe because the presence of cellulose-degrading bacteria, such as species of the families Ruminococaceae; Bacillaceae (the genus Bacillus) and Clostridia (the genus Clostridium), was reduced in the acidic soils.
4.4.4 The soils 2 and 3 were rich in the Alpha-, Beta- and Delta-Proteobacteria (i.e., sulphate reducing bacteria), which can only decompose monomeric organic matter (e.g., glucose, acetate, organic acids). In particular, they lacked the cellulose degrading bacteria necessary for the effective degradation of jute and coir, which are macromolecule materials. Hence there was less degradation of their fibres in soils 2 and 3. This indicates that a biological investigation into the soil present in the field should be carried before using natural fibre drains, in order to clarify whether potential cellulose degrading bacteria exist in the soil, thus allowing the appropriate solution involving fibre drains to be selected.

4.4.5 An analytical approach to predict soil consolidation incorporating multiple forms of drain degradation $q_w$ over time has been proposed. Evaluation of the solution considering an initial intact period showed a deviation ($> 5\%$) in the dissipation of excess pore pressure compared to the approach using an immediate reduction of discharge capacity; suggesting the consolidation of soil induced by a biodegradable drain can now be predicted more realistically.

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Chapter 05 Permeability Capturing Micro-Features

Chapter 5 PERMEABILITY OF NATURAL FIBRE DRAIN CAPTURING MICRO-FEATURES


5.1 Introduction

Synthetic materials have been used extensively in many geoengineering applications such as reinforcement (Yin, 1997; Zhan and Yin, 2001), separation (Arulrajah et al., 2009), and drainage (Chu et al., 2009; Indraratna et al., 2012; Kelly, 2014) but these polymer-based solutions have raised concern from ecological and biological perspectives because polymeric materials are resistant to biodegradation (Nicholson, 2006) and thus harmful to the natural environment (Gregory and Andrady, 2003). This is why geomaterials made from natural fibres such as jute and coir have received favourable attention in recent times such as erosion control (Vinod and Minu, 2010; Midha et al., 2014); reinforcement (Babu and Vasudevan, 2007; Subaida et al., 2009; Vinod and Bhaskar, 2012); and soft soil improvement (Jang et al., 2001; Beena and Babu, 2008; Asha and Mandal, 2015; Indraratna et al., 2016). These naturally occurring materials not only have beneficial engineering characteristics, they are also biodegradable over time. More importantly, natural fibres are abundant in many developing regions, particularly in South and Southeast Asian countries, so a wider application of these materials can certainly bring considerable social and economic benefits to local populations.

The most commonly used natural fibres in geoengineering are jute and coir, with India
and Sri Lanka being the major producers of coir fibre, followed by Thailand, Vietnam, the Philippines and Indonesia (Ali, 2010), while more than 90% of the world’s jute is manufactured in Bangladesh, China, India and Thailand (Rahman, 2010). Coir fibre extracted from coconut husks contains more than 40% lignin (Gupta, 2011), making it more robust and durable than other natural fibres such as jute which contains more than 80% cellulose and only around 12% lignin (Som et al., 2009). Note that more lignin means the better the fibre can resist biodegradation. The durability of natural fibres also depends on the environmental conditions such as humidity, temperature, acidity and biological properties of soil (Kim and Cho, 2008; Saha et al., 2012). Other natural fibres such as straw, bamboo, and hemp are abundant in many agricultural regions such as Vietnam and Thailand.

Most natural fibres are used for filtration and drainage based on their distinct hydraulic conductivity. There are numerous studies (Sullivan, 1942; Gebart, 1992; Xu and Yu, 2008; Yazdchi et al., 2012) addressing the hydraulic behaviour of fibrous media, but most of them only considered idealised arrangements of fibres such as quadratic and hexagonal parallel arrangements (Gebart, 1992; Nakayama et al., 2007; Tamayol and Bahrami, 2009), whereas the natural fibres used in geoengineering have a more complex porous structure where the fibres are disordered and twisted (Nguyen and Indraratna, 2017a). Furthermore, when investigating the hydraulic behaviour of natural fibre drains, many studies only concentrated on the macro perspectives such as the discharge capacity of the whole drain (Venkatappa Rao et al., 2000; Asha and Mandal, 2012), while ignoring the micro-aspects such as the shape, size and uniformity of fibres which can have a significant influence on the permeability of fibrous media (Williams et al., 1974; Ozgumus et al., 2014). It is therefore necessary to study the micro-characteristics of natural fibres arranged in a more practical form and examine how it influences their hydraulic conductivity.

To predict the permeability of a porous medium, the analytical method proposed by
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Kozeny (1927) and later modified by Carman (1937) (known as Kozeny-Carman (KC) method) is preferred in practice due to its computational simplicity. Note that this is a semi-empirical method which requires the Kozeny constant \( k_k \) to be determined according to the particular micro-features of the medium. While numerous studies have determined this constant for uniform porous media, not many have used this approach to the natural fibres used in geoengineering where the elemental particles are less homogenous. Because the constant \( k_k \) is very sensitive to the micro-characteristics of the medium (Xu and Yu, 2008; Ozgumus et al., 2014), how this coefficient varies over the micro-parameters and its implication to natural fibres such as coir and jute must be investigated.

This study therefore aims to clarify the hydraulic behaviour of typical natural fibres used in geoengineering such as jute and coir by an experimental scheme. Micro-analyses of fibre drains are carried out and the influence of micro-characteristics on the hydraulic conductivity of the drain is represented. The KC method is applied and validated with experimental results, and a suggestion about how to use this method in practice is made.

5.2 Analytical method to estimate the permeability of fibre drain

The permeability of a porous medium can be predicted by the Kozeny-Carman (KC) approach as follows:

\[
K = \frac{1}{k_k A_o^2} \frac{n_f^3}{(1 - n_f)^2}
\]  

[5.1]

where \( K \) is the permeability; \( n \) is the porosity; \( k_k \) is the so-called Kozeny constant which is determined empirically; \( A_o \) is the specific surface of the media defined as the ratio of the fluid-solid interfacial surface to the solid volume in a given fluid-solid system. If a medium consists of individual fibres in a certain arrangement, \( A_o \) actually becomes the ratio of the perimeter to the cross-sectional area of the fibres, so it actually varies with the shape of the fibre particles; for example, with cylindrical fibres Eq. [5.1] can be re-written as:


where \( d_{f,i} \) is the diameter of the fibre \( i \), and \( n_f \) is the number of fibre particles in the medium. If all the fibres have a uniform diameter (e.g., \( d_f \)), then can be simplified as:

\[
K = \frac{d_f^2}{16k_k} \left( \frac{n_f^3}{(1-n_f)^2} \right) \qquad [5.3]
\]

Although most studies agree that \( K \) is proportional to \( n_f^3/(1-n_f)^2 \), there is a certain variation when considering other parameters in the KC method. The most common preferences (Sullivan, 1942; Gutowski et al., 1987; Choi et al., 1998) are using the Kozeny constant \( k_k \) independently with the diameter \( d_f \), so that \( k_k \) varies with other micro-characteristics of the medium such as the porosity and fibre arrangement. Others such as Rodriguez et al. (2004) and Yazdchi et al. (2012) simplified the method further by combining \( d_f \) and \( k_k \) into one parameter which is also determined empirically.

Obviously Eq. [5.3] is applicable for idealised conditions where fibres are uniform, whereas Eq. [5.1] and [5.2] are much more complicated in determining \( A_o \) and the diameters of individual fibres \( d_{f,i} \) in the medium, so it is better to use an average diameter \( d_{f,a} \) to represent all of the single fibres. \( d_{f,a} \) can vary widely with fibres such as jute and coir, and with different manufacturing techniques, so a prior investigation is needed to obtain this representative parameter accurately before applying the KC equation. It is also important to note that the average diameter approach can lead to a certain inaccuracy in the predicted permeability because natural fibres such as jute and coir are clearly non-uniform, and therefore this can potentially result in a different behaviour of \( k_k \) compared to a conventional application of the KC method in homogenous particulate media.

Over the years an enormous effort has been made to determine \( k_k \) for fibrous media.
Studies such as Gutowski et al. (1987), Gebart (1992), and Li and Gu (2005) adopted a constant $k_k$ unchanged over varying porosity while others (Rahli et al., 1997; Choi et al., 1998; Xu and Yu, 2008) suggested a porosity-dependent $k_k$. Kyan et al. (1970) proposed an analytical solution incorporating micro-porous parameters into the calculation of $k_k$ such as porosity, diameter, and the tortuosity of fibre media. Numerous studies (Gutowski et al., 1987; Choi et al., 1998; Li and Gu, 2005; Yazdchi et al., 2012) also attempted to link $k_k$ to the tortuosity $t$ which is defined as the ratio of the actual flow path to the straight length of a fibre drain, as given by:

$$k_k = c_s to^2$$  \[5.4\]

where $c_s$ is the shape factor representing the influence of the cross-sectional shape of fibres, and $c_s$ is defined as the ratio between the surface area of the fibre to the surface area of a sphere with the same volume (Li and Gu, 2005). With cylindrical fibre, the shape factor reaches its minimum value ($c_s = 1$) where the tortuosity $t_o$ depends on how the fibres are arranged in the bundle. A perfectly parallel arrangement of fibres has the shortest fluid path, resulting in a unity of $t_o$. According to this approach, cylindrical fibres arranged in parallel have smallest $k_k$ and the highest permeability.

### 5.3 Experimental investigation into the permeability of fibre drain

#### 5.3.1 Fibre drain

A natural fibre drain which is actually a combination of individual fibres in a certain arrangement is usually employed for drainage where the fluid flows in the void between those fibres (Lee et al., 1994; Venkatappa Rao et al., 2000). At present there are a variety of fibre drains made from different natural fibres such as jute, coir, and straw, with either a circular or band shaped cross-section (Jang et al., 2001; Beena and Babu, 2008). Of the existing naturally occurring materials, coir and jute are the most preferable due to their favourable
engineering characteristics and abundance in developing regions. Despite such a variety of structures and materials, the discharge capacity of the whole drain relies on the hydraulic properties of its elemental fibre bundles. In this study, brown coir and jute fibres were used to generate elemental fibre drains which were then subjected to an experimental investigation into the hydraulic conductivity of the fibres.

Fig. 5.1 Fundamental bundles of jute and coir drains

In this study there were two basic fibre arrangements, non-twisted and twisted bundles (Fig. 5.1). The non-twisted bundles meant individual fibres were placed in almost parallel array without twisting, while fibres in the twisted structure were packed and twisted together around the longitudinal axis of the bundle, such that the larger the twisting angle, the more the fibres were tightened and pressed together. The fraction of fibre in a drain was approximately manipulated by the quantity of single fibres packed into the drain; the more
fibres were packed, the denser the bundle. In this current approach the fibres were placed randomly into a bundle while previous studies (Gebart, 1992; Nakayama et al., 2007) investigated fibres arranged in particular forms such as square and hexagonal arrays because in geoengineering applications the disordered arrangement of fibres is overwhelming.

![Distribution of the average diameter of jute and coir](image)

**Fig. 5.2** Distribution of the average diameter of jute and coir

To create a fibre drain for testing in a consistent manner to ensure reproducibility of results, individual fresh fibres (almost straight and longer than 150 mm) were selected and arranged in parallel. Two ends of the bundle were confined by a thin ring. The bundle was then placed in a long tube (4 mm inner diameter and 100 mm long) by pulling its end. While
one end of the bundle was fixed, the other end was rotated gradually, making the whole bundle twisted to the desired twisting angle. Two ends of the bundle were then trimmed to ensure that all fibres would have the same length (i.e., 100 mm). For non-twisted bundles, the twisting step was skipped. By this process, the fibre drains having different twisting angles were generated. In this study, there were 44 coir and 19 jute bundles generated for different objectives of the investigation.

The physical properties of jute and coir such as density and average diameter were determined in the laboratory using an optical microscope. Fig. 5.2 shows the size distribution of jute and coir fibres used in this study. The equivalent diameter of jute varied from 10 to 85 μm but more than 75% of the fibres were between 25 to 55 μm in diameter. The mean diameter of jute was 41.8 μm, which was within the common ranges reported by previous studies such as 54 μm by Defoirdt et al. (2010). Unlike jute, coir was much larger; its diameter ranged from 90 to 502 μm, with a mean value of 235 μm. The most popular size of coir fibre was from 150 to 300 μm, and this accounted for more than 70% of total fibres. The density of jute and coir were 1415 and 1105 kg/m³, respectively. These parameters were corroborated with those reported in previous studies (Defoirdt et al., 2010; Gupta, 2011).

Fig. 5.3 shows how the cross-sectional shapes of coir differed from jute. Coir had almost round cross-sections, while jute had very complex polygonal shapes that varied from square and rectangular, to irregular ones. These differences in the geometric features of jute and coir fibres resulted in drains with different porous characteristics.
5.3.2 Hydraulic conductivity test on fibre drains

Two approaches are generally used to determine the hydraulic conductivity of fibrous materials, either a unidirectional or radial flow (Sharma and Siginer, 2010). A fluid flow with a low injection pressure is used to ensure the fibres remain in a static condition by controlling either the velocity or pressure of the inlet fluid while the fluid is flowing. In this study the pressure controlled model which has been used commonly in previous studies (Sullivan, 1942; Williams et al., 1974; Rahli et al., 1997) due to its simplicity was adopted (Fig. 5.4).
A key objective of this study is to investigate the influence of micro-characteristics on the hydraulic behaviour of natural fibre drain. In this regard for the purpose of simplicity, the actual role of interaction between the soil and drain fibres (i.e. soil-drain interface effects) has not been quantified within the scope of this paper. However, it is noteworthy that for many in situ applications, the influence of soil-fibre drain interaction on the hydraulic behaviour of the drain can be a significant factor, and this will be evaluated in a future study.

The tube holding fibres drain used for hydraulic test had a smooth internal surface to minimise the friction that could affect fluid flow, and the inlet was connected to a constant head water tank. Moreover, manometers were used to measure the water heads at the inlet and outlet of the tube to an accuracy of 1 mm. The difference in pressure between the inlet and outlet of the tube was adjusted by changing the relative height between the tube and the water tank. Water flowed from the inlet through the fibre drain and was measured at the outlet of the tube under different heads of water. Based on the volume of water discharged at the outlet over time, the hydraulic conductivity of the fibre bundle was obtained. Note that the hydraulic gradient was determined with respect to the length of the fibre drain and the difference in water heads at two ends of the tube.

Fig. 5.4 Schematics of experimental model to determine hydraulic conductivity of fibrous drain
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The effect of friction between the walls of the tube and fluid on the discharge velocity of flow was evaluated by measuring the loss of water head between the inlet and outlet over varying discharge velocity when water was flowing through the vacant tube. The result showed an insignificant loss in the water head for medium and dense fibres, where the flow velocity was small and where the internal surface area of the tube was relatively insignificant compared to the total surface area of the fibres. However, for loose media (e.g., \( n_f > 0.85 \)), friction at the fluid-wall could account for approximately 12% and 31% of total water heads for jute and coir drains, respectively. Previous studies by Sullivan (1942) using 8.31 mm diameter and 50.5 mm long copper tube, and by Williams et al. (1974) employing a 5 mm diameter and 150 mm long glass tube also considered the effect of the boundary, and pointed out that this disturbance could be omitted for fine fibres but considerable for coarse fibres (i.e., \( d_f > 50 \mu m \)).

After the hydraulic test the fibres were subjected to a post-processing which enabled their micro-characteristics to be captured. The tube containing fibres was dried by gently blowing warm dry air through the tube. To maintain the original structure of the fibrous system after the hydraulic test, the fibre tube was then immersed into resin mixed with a hardener to cast samples. These samples holding micro-porous information of fibre bundles were then subjected to micro-analyses. Photos of the cross section of the hardened fibre tubes were taken with an optical microscope. The image analysis techniques available in the ImageJ software (Rasband, 2014) were implemented on these photos to obtain micro-porous properties of the drains such as the cross-sectional area of resin (void) and solid fibres; these parameters also enabled the porosity of the drain to be estimated. Note that the resin representing the voids of drain (Fig. 5.3) was much different in colour to solid fibres, making the determination of porosity easier by using area measurement techniques on ImageJ. The porosity of a bundle was measured at different positions, i.e., 2 ends and 1 at the middle of
the bundle and then an average value was used.

With respect to the water volume \( V_w \) obtained at the outlet of the fibre tube over time \( t \), the hydraulic conductivity \( k \) was determined by:

\[
k = \frac{V_w R_t}{i_h A_t t}
\]  

[5.5]

where \( R_t \) is the correction factor for the viscosity of water, depending on the water temperature (ASTM D4716, 2008); \( A_t \) is the interior cross-sectional area of the tube, and \( i_h \) is the hydraulic gradient. Note that in this experiment, fluid flow was investigated under a small difference in water heads to ensure laminar flow, while the discharge volume was measured at a steady state of flow. The water used in the experiment was approximately 19\(^\circ\) C, and in this condition the kinetic viscosity of water was 1.002x10\(^{-6}\) m\(^2\)/s (Massey and Ward-Smith, 2006).

5.4 Results and discussion

5.4.1 Discharge velocity over hydraulic gradient

![Graph](image)

Fig. 5.5 Variation of discharge velocity \( U_s \) over hydraulic gradient \( i_h \)

The discharge capacity of a drain must be considered with respect to the hydraulic
gradient at which it is measured (Chu et al., 2004). The variation of the discharge velocity (superficial velocity $U_s$) over the hydraulic gradient ($i_h$) of fluid flow recorded in the experiment for typical coir and jute fibre drains, including loose ($n_f > 0.8$) to dense ($n_f < 0.5$) media, is shown in Fig. 5.5. Here the larger the hydraulic gradient, the higher the discharge velocity. The relationship between $U_s$ and $i_h$ is almost linear when $i_h$ is small enough to maintain laminar flow where $U_s = k \times i_h$ (Darcy law). However, this relationship becomes non-linear when $i_h$ increases, which indicates that the flow would turn into a turbulent transition zone where the inertial part of the flow is larger. The turning point between the laminar and turbulent transition zones occurs earlier when the fibres are looser; for example, loose fibre drains have a turning point at $i_h = 0.3$ and $i_h = 0.5$ for coir and jute fibres, respectively, but this gradually increases as the porosity of the fibre drains decreases. This occurred because the looser fibres had a higher flow velocity, leading to a larger contribution of inertial flow. Note that the well-known Reynolds number ($Re = U_f L / \nu$ where $U_f$ is the flow velocity; $L$ is the characteristic length; $\nu$ is the kinetic viscosity) which is commonly used to evaluate the flow state, is proportional to the fluid velocity (Massey and Ward-Smith, 2006).

Previous studies (Akagi, 1994; Rawes, 1997) have suggested that the largest hydraulic gradient needed to maintain laminar flow in discharge capacity tests of conventional drains should be from 0.1 to 1, depending on the features of the testing models such as scale, confining pressure, and drain characteristics. In this study the hydraulic conductivity of fibre drains was considered in conjunction with laminar flow, so that the discharge velocity was only adopted at small values of $i$ (i.e., $i_h < 0.3$ for loose fibres and $i_h < 1$ for medium and dense fibres).

5.4.2 Influence of the size of fibres in drain

The average diameter of natural fibres varies widely from several micrometres (e.g.,
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silk) to hundreds of micrometres (e.g., coconut coir), and that can cause a difference in their hydraulic behaviour. To clarify how differences in the size of fibres could affect the hydraulic behaviour of drains, only coir fibre, which had been shown to be more homogeneous and larger in size than jute, was used for this investigation. Also, only coir fibres were used to remove any influence that the difference in the shape and surface of fibre between jute and coir might have on the experimental result. Since the diameter of individual fibres in a bundle can be varying widely (Fig. 2), the dispersion in diameter of a fibre medium also needs evaluating through the coefficient of variation \( a_v \) which is defined as the ratio of the standard variation to the mean fibre diameter, such that a smaller \( a_v \) indicates more uniform fibres in the drain.

The mean diameter of fibres in a bundle

Fig. 5.6 Coir drains with different fibre diameters: a) Big size \( d_{fa} = 376 \mu m; n_f = 0.59 \); b) Medium size \( d_{fa} = 239 \mu m; n_f = 0.55 \); c) Small size \( d_{fa} = 155 \mu m; n_f = 0.62 \)

For this aspect of the investigation, hydraulic tests were carried out on coir bundles having different mean (average) diameters. Three sets of fibres with mean diameters of \( d_{fa} = 155, 239 \) and \( 376 \mu m \) were generated (Fig. 5.6), and a non-twisted type of drain was used. Note that for each level of mean diameter, hydraulic test was conducted over varying porosity (different bundles). Fibres in a bundle in this investigation were highly uniform in diameter; particularly the coefficient of variation varied in a small range from 8.7 to 11.2 % for all
The influence that the mean diameter of fibres in a drain has on its hydraulic conductivity is shown in Fig. 5.7. It is interesting that the drain formed by the larger diameter fibres results in a higher permeability for the same porosity. For example, with \( n_f = 0.6 \), the hydraulic conductivity of the drain is \( 3.1 \times 10^{-3} \) m/s for the smallest fibres, and this increases to \( 9.0 \times 10^{-3} \) m/s and \( 21 \times 10^{-3} \) m/s when \( d_{f,a} \) increases to 239 and 376 \( \mu \)m, respectively. The gaps between the 3 curves are larger when the fibre drain is denser. Particularly when the fibre drain is loose (\( n_f = 0.85 \)) and \( d_{f,a} \) increases from 155 \( \mu \)m to 239 and 376 \( \mu \)m, the hydraulic conductivity is 1.74 and 2.39 times higher, respectively. However this increase in permeability is larger at \( n_f = 0.55 \) where \( k \) increases by a factor of 2.89 and 7.78, respectively for the same increments in fibre size. This dependence of hydraulic conductivity on the size of fibre was understandable because the drain with a larger mean diameter had a smaller contact area between the fibres and fluid despite the constant fibre fraction over different sets of fibre drain, leading to the drain having a higher permeability.

![Fig. 5.7 Influence of fibre size on the hydraulic conductivity of coir fibres](image_url)
In this investigation, fibre drains made from coir with different ranges of uniformity ($a_v$) but the same mean diameter and porosity were generated without twisting. Fig. 5.8 shows how the diameter uniformity of fibres in a drain can affect its hydraulic conductivity, and although fibre drains have almost the same porosity and mean diameter varying in a small range from 227 to 254 µm, the greater their uniformity (lower $a_v$) the higher the permeability of the drain. For example, when $n_f = 0.65$, $k$ decreases from $2.0 \times 10^{-2}$ m/s at $a_v = 10\%$ to $1.4 \times 10^{-2}$ m/s and $0.71 \times 10^{-2}$ m/s at $a_v = 20\%$ and $30\%$, respectively. This decrease in $k$ is sharper when the range of fibre size in the drain is wider, particularly in a denser fibre drain. When $n_f = 0.45$, $k$ decreases by a factor of 1.7, from $2.1 \times 10^{-3}$ m/s to $1.2 \times 10^{-3}$ m/s when $a_v$ increases from 10\% to 20\%, but there is a more severe reduction by a factor of 5.37 as $a_v$ reaches 30\%. It is also interesting that the influence of fibre uniformity on the permeability of the drain is less as the drain becomes looser. When $n_f = 0.85$, $k$ decreases slightly from $1.8 \times 10^{-1}$ m/s at $a_v = 10\%$ to $1.5 \times 10^{-1}$ m/s and $1.03 \times 10^{-1}$ m/s at $a_v = 20\%$ and $30\%$, respectively.

Fig. 5.8 Influence of the uniformity on the hydraulic conductivity of fibres
The dispersion in the size of fibres affected the permeability of the drain because when the size of fibres was distributed over a wider range, more fibres with a smaller diameter, which had been shown to reduce the permeability of fibre media, were created. As a result, the less uniform fibres had the greater frictional contact area between fibres and fluid, leading to a lower hydraulic conductivity in the drain.

5.4.3 Hydraulic conductivity of jute and coir drains

Comparison of hydraulic behaviour of jute and coir fibres

Fig. 5.9 Hydraulic conductivity over porosity of jute and coir with different twisting angle

Fig. 5.9 shows how the hydraulic conductivity of jute and coir fibres is related to the porosity of a drain. In this series of hydraulic tests, the mean diameters of fibres in different drains were noted to ensure their deviations were less than 5% for coir and 10% for jute to minimise the influence of fibre size, as discussed in previous sections of this paper. The coefficient of variation $\sigma_v$ in diameter of fibres in a drain varied from 25.6 to 31.3 % and 36.2 to 44.8 % for coir and jute, respectively. The figure shows that as porosity decreases, so the permeability becomes smaller, but the slope of the reduction curves is increasing over the
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decrease in porosity. The hydraulic conductivity of the drain gradually decreases when the fibre fraction is between the loose and medium ranges, but this reduction becomes sharper when fibres are denser \( (n_f < 0.5) \).

There is a clear difference between the hydraulic conductivity of jute and coir drains, as shown in Fig. 5.9. For the same porosity, coir fibres result in an apparently higher permeability than the jute fibres. The \( k \) of the coir media decreases from 0.21 m/s at \( n_f = 0.9 \) to 3.5x10\(^{-4} \) m/s at \( n_f = 0.45 \), whereas the jute fibres show \( k \) decreasing from 0.015 to 4.2x10\(^{-6} \) m/s for the same range of porosity. The coir fibres also resist a reduction of porosity better than jute fibres; for example, when porosity falls from 0.9 to 0.45, the \( k \) of the coir decreases by a factor of 600, but this parameter of the jute decreases by a much greater factor of 3571. This indicates the distinct advantage in hydraulic conductivity that coir fibres have over jute fibres.

The difference between the micro-characteristics of jute and coir fibres could explain the deviation in hydraulic behaviour between jute and coir drains. First, coir fibres used in this investigation had an average diameter of 235 \( \mu \)m which was much larger than one of jute, i.e., \( d_{fa} = 42.0 \) \( \mu \)m. As shown above, the medium composed of smaller diameter fibres had a greater surface area though the fibre fraction of media that was constant, leading to increased friction between the fluid and the fibres. In addition, jute fibre had a larger dispersion in size than coir. The average value of \( a_v \) estimated from the distribution in diameter of fibres (Fig. 5.3) was 27.1% and 40.3% for coir and jute, respectively, and that indicated a much wider range in diameter of jute fibres used in this study. This explained why jute drains had a much lower permeability than coir drains.

Moreover, a micro-observation of the cross-sectional shape of jute and coir fibres (Fig. 5.3) indicates that jute fibre has irregular shapes, particularly polygonal ones, while the coir fibre is almost round, and thus having the smallest perimeter of those with the same
cross-sectional area. For example, the perimeter of a square and hexagon is 1.13 and 1.05 times larger than a circular one with the same area. By referring to Eq. [5.4], the shape factor \( c \) of jute was thus greater than that of coir. This difference in geometric features contributed to jute having a larger fluid-fibre contact area than coir, and making the jute drain much lower in permeability than its counterpart.

**Influence of the microstructure of fibre drain**

In this study, two structural types of fibre drain including non-twisted and twisted fibres were investigated. The effect that the twisting angle has on the permeability of a fibre drain is shown in Fig. 5.9, where for the same porosity, the larger the twisting angle the lower the permeability of the drain. For example, with \( n_f = 0.5 \) the non-twisted coir fibres have a hydraulic conductivity of \( 8.5 \times 10^{-4} \) m/s while the fibre drains with a twisting angle of 15° and 25° have a lower hydraulic conductivity, i.e., \( 6.1 \times 10^{-4} \) m/s and \( 4.8 \times 10^{-4} \) m/s, respectively. The same behaviour also occurs with jute fibres, but it is more apparent; when \( n_f = 0.6 \), the jute drain without twisting has \( k \) of \( 7.1 \times 10^{-5} \) m/s but this decreases to \( 3.8 \times 10^{-5} \) m/s and \( 2.2 \times 10^{-5} \) m/s when the jute is twisted at 15° and 25°, respectively. However, the influence that the twisting angle has on the permeability of a fibre drain is not as significant when the fibres are looser, in fact it can be ignored when \( n_f > 0.7 \) and 0.8 for both coir and jute drains.

The fibres in the non-twisted structure (Fig. 5.1a) were packed randomly without twisting them around the axis of the drain, thus making porous channels along the fibres shorter than those formed in the twisted structure where the fibres created an angle to the axis of the bundle (Fig. 5.1b). This difference resulted in a more complex and tortuous fluid path, and as a consequence the hydraulic conductivity of the twisted drain was smaller. Assuming that the straight length of the drain with non-twisted fibres would be the shortest distance for fluid to travel, then the fluid path in fibres twisted at angle \( \theta \) was \( 1/\cos(\theta) \) longer than the non-twisted case, and therefore the larger twisting angle caused a greater tortuosity and...
resulted in lower permeability (see Eq. [5.4]).

Comparison with other studies

Fig. 5.10 Normalised permeability of jute and coir fibres in comparison with other studies

The permeability of jute and coir fibres without twisting was normalised to the average diameter of the fibres and then compared to those reported by previous studies (Fig. 5.10). In this figure, a number of studies about the permeability of fibrous media are adopted, including analytical solutions such as solving the Navier-Stokes equations (Happel, 1959), modifying the KC method (Gebart, 1992), incorporating the parabolic distribution of fluid velocity into the Stokes equations (Tamayol and Bahrami, 2009), and the numerical method by coupling the Finite Volume Method and the Discrete Element Method (Nguyen and Indraratna, 2016), as well as experimental work (Rahli et al., 1997). It is clear that the differences between the results shown in Fig. 10 for $n_f > 0.75$ are insignificant, but they quickly begin to deviate when $n_f < 0.7$, especially the normalised permeability of jute and coir fibres, which become much lower than those reported from previous studies when $n_f < 0.5$. The experimental work carried out by Rahli et al. (1997) using uniform cylindrical fibres
with a diameter of 150 μm is the closest to the permeability curve of the coir obtained in this study.

There were several differences in the micro-characteristics of fibrous media in those studies that could clarify such a deviation in hydraulic behaviour. First, previous studies used an idealised parallel arrangement of fibres where the fluid only flowed in parallel channels, whereas the fibres in this study were not completely parallel (Fig. 5.1). Second, the analytical and numerical models adopted in this comparison considered flow in a particular unit template of fibres such as quadratic and hexagonal forms, whereas in this study the jute and coir fibres were packed randomly. Moreover, cylindrical fibres with circular cross-section were used in previous works but the fibres used in the current study, especially jute, did not have a circular cross-section. Also, the perfectly uniform fibres with only a single size ($a_v = 0$) used in previous studies differed from those in jute and coir in the current work represented above, leading to a considerable difference in their fluid-fibre contact area. The denser fibres made this deviation more apparent.

It was also noted that although the diameter-normalised permeability was used to remove any influence that the difference in the size of fibre between jute and coir would make on the results, there was still a deviation between the permeability curves of jute and coir, particularly as fibres became denser ($n_f < 0.65$); this occurred because the differences in the shape and dispersion in size between the jute and coir fibres were still valid in this approach. Note that when natural fibres used in practice, their shape and size varies, so that using idealised conditions with cylindrical and parallel fibres is not realistic from a geoengineering perspective.

5.4.4 Prediction of hydraulic conductivity by the Kozeny-Carman (KC) approach

By applying the KC method described in Eq. [3], the hydraulic conductivity of coir and jute drains was estimated and compared to those measured in the experimental part of
this study (Fig. 5.11). In this application the average diameter $d_{f,a}$ varied slightly from 39.7 to 45.7 \(\mu\)m, and 224 to 243 \(\mu\)m for jute and coir drains, respectively over different levels of porosity and the Kozeny constant $k_k$ was used independently of the porosity of the drain. The prediction by the KC approach using $k_k = 10$ matches the experimental result for a coir drain having $a_v = 20\%$ in the porosity range from 0.45 to 0.9 quite well; the deviation between the two approaches can be ignored in this range but it increases when the porosity of the drain is beyond the values where the predicted $k$ becomes much higher ($n_f > 0.9$) or lower ($n_f < 0.45$) than the experimental one.

![Fig. 5.11 Prediction of hydraulic conductivity by KC method in comparison with experiment](image)

The analytical prediction is less accurate when uniformity in the size of the fibres decreases. For $a_v = 30\%$, the prediction by KC method with $k_k = 12$ is very accurate but only for $0.55 < n_f < 0.90$. When the fibre drain is denser or looser, the predicted curve deviates significantly from the experimental one; in fact when $n_f = 0.4$, the $k$ measured in the experiment is $1.9 \times 10^{-4}$ m/s but the predicted value is much higher (i.e., $6.1 \times 10^{-4}$ m/s).

Those jute drains with a wider dispersion ($a_v = 40\%$) in fibre size and smaller
permeability meant that the prediction by KC method using a porosity-independent $k_k$ was less accurate than for coir drains. When $k_k = 9$, the predicted curve for jute matches the experimental result for $0.63 < n_f < 0.95$ quite well, and then begins to deviate significantly when $n_f < 0.6$. The greater input of $k_k$ enables the analytical curve to be closer to those measured by the experimental approach in the denser fibres, but it is not as accurate in the loose media. This limitation of the KC approach using a constant $k_k$ over the variation of porosity meant that it was only acceptable in a certain range of porosity.

5.4.5 *Kozeny constant $k_k$*

To improve the accuracy of the KC method at predicting the permeability of fibrous media, a flexible Kozeny constant which is functional to the micro-characteristics of fibre drain must be used. The dependence of $k_k$ on particular micro-parameters such as porosity, the structure of drains (non-twisted and twisted fibres), and the size and uniformity in size of fibres, was back-analysed on the basis of the experimental results represented in previous sections and is shown in Fig. 5.12. Fig. 5.12a shows how $k_k$ varies over the different porosities of drains for non-twisted and twisted fibres, including jute and coir. The variation of $k_k$ for non-twisted fibres is insignificant, particularly from 6 to 10 with a range of porosity of $0.65 < n_f < 0.9$. The difference between the $k_k$ of jute and coir is not evident in this range, but $k_k$ increases rapidly and the deviation between jute and coir becomes more apparent when the medium is denser or looser. At $n_f = 0.45$, $k_k$ reaches almost 30 for coir and 80 for jute. Moreover, the influence of the drain structure (twisted and non-twisted fibres) on $k_k$ can be ignored for loose fibres but it increases considerably as the porosity decreases; in the fact the gaps between the $k_k$ of non-twisted and twisted fibres are completely different when $n_f$ is less than 0.6 for coir and 0.75 for jute.
Fig. 5.12 Variation of \( k_k \) over the porosity of drain with different micro-porous parameters: \( a) \) structure and type of fibres; \( b) \) size of fibres; \( c) \) uniformity of fibres; and \( d) \) in comparison to other studies

The influence of fibre size on \( k_k \) is shown in Fig. 5.12b. Note that in this investigation, the uniformity of fibres was almost the same and had insignificant influence on the results. It is interesting that the effect of fibre size on \( k_k \) is not consistent over the variation of porosity, for example, when \( n_f > 0.64 \), the biggest diameter fibres have the highest values of \( k_k \) but this trend becomes opposite when \( n_f < 0.64 \). The figure also indicates that the three curves of \( k_k \) all show their bottom at different degrees of porosity, depending on the size of fibres. The \( k_k \) of the smaller fibres reaches the bottom at a larger porosity (e.g., 0.77 for \( d_{f,a} = 376 \mu m \) and 0.43 for \( d_{f,a} = 155 \mu m \)), and with a sharper drop, but the influence of fibre size on \( k_k \) only becomes critical when the fibre fraction enters the dense zone (i.e., \( n_f < 0.5 \)).
There is an apparent contribution by the dispersion in the size of fibre to the value of $k_k$ as shown in Fig. 5.12c. As more uniform fibres are created in the drain, a more stable and lower value of $k_k$ is obtained, in fact the fibre drain with $a_v = 10\%$ shows its $k_k$ decreasing quickly from almost 17 to around 3 as porosity decreases from 0.93 to 0.72, but it does not change much in the denser fibres. However, a wider range of fibre sizes makes the $k_k$ vary more, for example, with the least uniform fibres ($a_v = 30\%$), $k_k$ is increasing continuously from 7 at $n_f = 0.85$ to 60 at $n_f = 0.35$, and the $k_k$ curve also reaches a lower bottom as fibres are more uniform. The minimum value of $k_k$ increases from 2.8 to 5.1 and 7 when the uniformity declines from $a_v = 10\%$ to 20 and 30\%, respectively.

A number of studies (Sullivan, 1942; Kyan et al., 1970; Rahli et al., 1997; Choi et al., 1998) have investigated the relationship between $k_k$ and porosity for longitudinal flow through a fibrous media. Sullivan (1942) and Kyan et al. (1970) have shown that $k_k$ decreases sharply as the porosity decreases from a very loose to a medium state ($n_f > 0.85$), and then stabilises in the medium to dense range ($0.45 < n_f < 0.8$). Rahli et al. (1997) and Choi et al. (1998) also found that $k_k$ increases rapidly when the porosity turns into the very dense fibre zone ($n_f < 0.35$). Other studies (Gutowski et al., 1987; Gebart, 1992) have adopted smaller constant values of $k_k$ (i.e., from 1 to 2.5) for flow along parallel homogeneous fibres. Those findings were made in the same condition that fibres were highly to totally uniform ($a_v = 0$) and ideally arranged in parallel. As Fig. 12c and 12d show, the current $k_k$ for fibres with a high uniformity ($a_v = 10\%$) agrees with those reported in previous works. This comparison reinforces the finding in this study that more uniform fibres result in smaller values of $k_k$ which are stable in the range from medium to dense fibres ($0.4 < n_f < 0.8$).

5.5 Conclusions

An intensive laboratory investigation into the influence of the micro-features of natural fibre drains on hydraulic conductivity was carried out in this study. Jute and coir were used to
create fibre drains which were then subjected to hydraulic conductivity testing. A number of governing micro-parameters such as the shape, size, and the twisting feature of fibres were addressed, and the following conclusions can be drawn:

5.5.1 The drain made from larger fibres that generated a smaller fluid-fibre contact area, had a higher hydraulic conductivity. Coir having larger average diameter \( d_{fa} = 235 \) \( \mu \text{m} \) compared to jute \( d_{fa} = 41.8 \) \( \mu \text{m} \) resulted in a significantly greater hydraulic conductivity for the same porosity.

5.5.2 The more the fibre was uniform in size, the greater the hydraulic conductivity. For the same porosity \( n_f = 0.45 \) and average diameter \( d_{fa} = 235 \) \( \mu \text{m} \), the hydraulic conductivity of the coir drain decreased from \( 2.1 \times 10^{-3} \) to \( 0.39 \times 10^{-3} \) m/s as the uniformity of fibre decreased from \( a_v = 10 \) to \( 30\% \), respectively. Generally jute had a larger size dispersion \( a_v = 40.3\% \) than coir \( a_v = 27.1\% \), leading to its lower hydraulic conductivity.

5.5.3 The cross-sectional shape of jute was almost polygonal, while that of coir was nearly round, which meant that jute had a larger shape factor that created a larger fluid-fibre contact area, and as a consequence, jute drains were less permeable than coir drains.

5.5.4 Twisting fibres made fluid flow in the drain more complex and increased its tortuosity; for example, the hydraulic conductivity of the drain with a 25° twisting angle was more than 30% lower than the drain without twisting in a certain range of porosity (i.e., \( n_f < 0.7 \) for coir and \( n_f < 0.8 \) for jute).

5.5.5 The analytical Kozeny-Carman (KC) approach using a porosity-independent constant \( k_k \) showed an acceptable degree of accuracy at predicting the hydraulic conductivity of natural fibres (jute and coir) in a certain range of porosity, but this acceptable range of porosity decreased with a larger \( k_k \) when fibres were less uniform. The KC method in particular was valid for a coir drain in the porosity range: 0.45 to 0.9 with \( k_k = 10 \).
and $a_v = 20\%$; 0.55 to 0.9 with $k_k = 12$ and $a_v = 30\%$, and for a jute drain in a porosity range from 0.63 to 0.95 with $k_k = 9$ and $a_v = 40\%$.

5.5.6 The micro-features of fibrous media such as porosity, size, the uniformity of fibres, and the arrangement of fibres in a drain (non-twisted and twisted fibres) had a significant influence on the Kozeny constant $k_k$. Generally, $k_k$ decreased to a minimum level before increasing continuously while the porosity of the drain was decreasing from 0.95 to 0.3. Fibres that were twisted more resulted in a larger magnitude of $k_k$, while fibres with a higher uniformity led to a much lower and more stable value $k_k$ (e.g., 3-4 with $a_v = 10\%$ for coir drain).

5.6 Acknowledgement

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Chapter 6 HYDRAULIC BEHAVIOUR OF PARALLEL FIBRES UNDER LONGITUDINAL FLOW – A NUMERICAL TREATMENT


6.1 Introduction

Fibrous porous materials have played an important role in a wide range of geoengineering applications, particularly in filtration, separation and drainage that are mostly related to the hydraulic conductivity of material. However, for many groups of fibres, especially for natural ones, the characteristics of hydraulic conductivity are not consistent due to their unstable porous structure, and that creates significant challenges in designs and applications. The long standing topic of seeking a comprehensive and flexible modelling technique for fibrous materials has received numerous concerns over the past decades. Most analytical approaches such as Gutowski et al. (1987); Gebart (1992); Yazdchi et al. (2011b) estimate hydraulic conductivity by referring to the classical Kozeny-Carman concept which states that permeability depends on the porous characteristics, based on an assumption that a porous material is analogous to a system of capillaries channelled along the direction of flow and diameter. Note that although the Kozeny-Carman equation is applicable in a wide range of isotropic porous materials, it needs significant modification before it can be applied to unidirectional materials where transverse flow is significantly more constricted than longitudinal flow (Gebart, 1992). For flow along a fibrous drain, a direct application of the KC equation is usually still acceptable (Sullivan, 1942; Gebart, 1992).
In this equation, the coefficient $k_k$ is called the Kozeny constant that accounts for the geometric characteristics of the porous media; $n_f$ is the porosity, and $d_h$ is the pore hydraulic diameter estimated from:

$$d_h = \frac{4}{A_o} \frac{n_f}{1 - n_f}$$  \[6.2\]

In Eq. [6.2], $A_o$ is the specific surface of the media and is defined as the ratio of the fluid-solid interfacial surface to the solid volume in a given fluid-solid system.

In this approach, the determination of Kozeny constant $k_k$ is the most controversial issue because it is mainly influenced by the geometric characteristics of porous media that are hard to define. Many previous studies have indicated a large range of Kozeny constant; for instance, Sullivan (1942) carried out a series of laboratory studies and summarised that $k_k$ of bundles of parallel fibres ranged from 0.806 for densely packed drill rods, with an $n_f$ of 0.093, to 10.57 for bundles of very loose wool fibres ($n_f = 0.98$). Despite efforts to build a comprehensive and robust analytical solution to predict the permeability of fibrous materials, most current formulations are inherent in the Kozeny-Carman concept which requires the empirical constant $k_k$ to be determined. Ozgumus et al. (2014) carried out an impressive review surrounding the determination of Kozeny constant $k_k$, and they concluded that although $k_k$ can be suggested either as a constant or a function of porosity, the effect of porous characteristics on $k_k$ has not been well clarified.

Attributed to the rapid development of computer technology in recent decades, the numerical solution for fluid transport through fibrous porous media has gained more attention (Gebart, 1992; Chen and Papathanasiou, 2007; Tamayol and Bahrami, 2008; Yazdchi et al., 2011b). The flexibility of being able to describe geometric structures and remove the Kozeny
constant in numerical approaches is obviously beneficial for practical designs and applications. Although various efforts to model the hydraulic conductivity of fibrous materials have been made over the past few decades, most current approaches assume the flow of fluid through a specific preform of porous media to be unchanged during simulation. The fibres in these models are actually treated as part of the boundary system which is normally assigned a constant set of parameters in the whole computation, but for many types of fibrous materials, especially for natural soft and light fibres, their fibrous structure is sensitive to external forces that cause variations in the pore characteristics, including inter-fibre distance, porosity, and effective flow path. Therefore, a framework which can simultaneously capture the behaviour of fluid and fibres is essential.

In recent times, the Discrete Element Method (DEM) has revealed its capacity to model the behaviour of material on the basis of analysing individual particles. Indeed, DEM has been used in a number of fields such as in applications to granular materials (Cundall and Strack, 1979; Cheng et al., 2003; Bertrand et al., 2005) and rock mechanics (Potyondy and Cundall, 2004; Cho et al., 2007). However, many studies (Zeghal and El Shamy, 2004, 2008; O'Sullivan, 2011) have shown that for a considerable number of geoengineering problems such as erosion, liquefaction which include two or more phases or interacting sub-systems, independently solving one phase or system is not sufficient and a consideration of the fluid-particle interaction is essentially required. This is why a great deal of effort has been put into describing particle-fluid interaction with major references to two approaches, namely the two-fluid model and coupling Computational Fluid Dynamics (CFD) with DEM (Zhou et al., 2010). In the CFD-DEM approach, DEM depicts the motion of discrete solid elements in parallel and interacting with the fluid flow simulated by CFD. Due to its major advantages, particularly in modelling fluid-solid systems, the coupled CFD-DEM has been recently applied to a variety of problems such as fluidisation, pneumatic conveying, pipeline flow, and
gas cyclone, where a thorough review was carried out by Zhu et al., (2008). Although coupling CFD-DEM is still a state of the art simulation technique, it is a cost effective tool to numerically describe various mechanics and engineering problems.

In this paper, an application of CFD-DEM coupling on modelling the hydraulic behaviour of fibrous materials with respect to the fluid-fibre interaction is described. The fibres were considered to be distinct solid elements while the fluid flow was treated in conjunction with the continuity and conservation concepts of Navier-Stokes equation. A neutral framework called CFDEM was employed to exchange and update information between DEM and CFD platforms in every pre-defined number of time steps. Based on such a numerical scheme, a promising technique to simulate fluid-fibre system was then proposed.

6.2 Theoretical background of coupled CFD-DEM approach

The first application of the CFD-DEM coupling technique was carried out by Tsuji et al. (1993) to model the inviscid flow of gas through porous media while considering particle motion in two dimensions. In this work, particle motion was governed by Newton’s law with respect to Discrete Element Method (Cundall and Strack, 1979) in the micro-scale, while the Navier-Stokes equation was used to describe the flow of gas in a macro-scale. Encouraged by this interest, many researchers have improved the original CFD-DEM coupling technique and applied it to a number of fluid-particle problems as summarised by Zhu et al. (2008).

The keystone of this coupling technique is the inter-exchange of motion as well as interaction forces between two phases to ensure that the fluid and particles behave in conjunction with each other. The total fluid-particle interaction force $F_f$ represents all the forces of fluid acting on particles that might include the pressure gradient force, the viscous force, the virtual mass or added force, the Basset force and lift forces (Zhou et al., 2010). Selecting components of $F_f$ depends on the nature and specific conditions of each problem. The coupling process responsible for phase to phase communication is managed by a mutual
framework called CFDEM that was developed by Goniva et al. (2010). Along the same time frame, while the particle motion is handled by a DEM framework named LIGGGHTS (Kloss and Goniva, 2010), the fluid behaviour is governed by OpenFOAM (www.openfoam.com). LIGGGHTS is coupled with OpenFOAM on the basis of different theoretical backgrounds that are described below.

6.2.1 Governing equation of particles and fluid

In the DEM proposed by Cundall and Strack (1979), the motion of a certain particle $i$ including translation and rotation, is governed by the following equations that are based on Newton’s second law.

\[
m_i \frac{dU_{p,i}}{dt} = \sum_{j=1}^{n_{c}^i} F_{c,ij} + F_{f,i} + F_{g,i}
\]

\[
l_i \frac{d\Omega_{p,i}}{dt} = \sum_{j=1}^{n_{c}^i} M_{c,ij}
\]

where $m_i$ and $l_i$ are the mass and inertia moment of particle $i$, respectively; $U_{p,i}$ and $\Omega_{p,i}$ are the translational and angular velocities of particle $i$; $F_{c,ij}$ and $M_{c,ij}$ are the contact force and torque exerting on particle $i$ by particle $j$ (or walls) while $n_{c}^i$ is referred to as the number of total contacts of particle $i$. The inter-particle contact behaviour is described by the either linear Hooke or non-linear Hertzian contact law which is adopted into DEM with respect to Coulomb’s friction law and the concept of particle overlap during collisions (Cundall and Strack, 1979). $F_{f,i}$ is the total fluid-particle interaction force acting on particle $i$ and $F_{g,i}$ is the gravitational force.

The governing equation employed in CFD is the locally averaged Navier-Stokes equation which describes the behaviour of pressure and velocity fields in the scale of a fluid.
cell. As described in past literature (Zhu et al., 2007; Zhou et al., 2010), there are two common distinct formulations of fluid flow equations, i.e., Model A and Model B. Model A assumes that the pressure is shared by the fluid and solid phases, while Model B only considers the fluid. Most investigations reported by Zhu et al. (2007) and Zhou et al. (2010) showed there was an insignificant difference between these two models, although Model A was more preferable, as noted by Zhou et al. (2010) and O’Sullivan (2011). In this study, Model A which incorporates the effects of particle volume fraction and distribution on pressure drop, was adopted.

$$\frac{\partial n_f}{\partial t} + \nabla \cdot (n_f U_f) = 0 \quad [6.5]$$

$$\frac{\partial (\rho_f n_f U_f)}{\partial t} + \nabla \cdot (\rho_f n_f U_f U_f) = -n_f \nabla p - f_p + \nabla \cdot (n_f \tau_f) + n_f \rho_f g \quad [6.6]$$

where $U_f$ and $p$ are respectively, the velocity and pressure of fluid; $\tau_f$ and $\varepsilon$ denote the viscous stress tensor and porosity of computational fluid cell, respectively; $\rho_f$ is the fluid density and $g$ is the gravity constant; $f_p$ in Eq. [6.6] is referred to as the mean volumetric particle-fluid interaction force exerted on the fluid cell by particles within the cell. The computation of $f_p$ is described by Eq. [6.7] with respect to the weight factor $\omega_{i,\zeta}$ which represents the volumetric portion of particle $i$ resided in cell $\zeta$.

$$f_{p,\zeta} = \sum_{i=1}^{n_{p,\zeta}} \omega_{i,\zeta} \left( \frac{F_{p,i}}{V_{c,\zeta}} \right) \quad [6.7]$$

In the above, $F_{p,i}$ is the total force acting on particle $i$; $V_{c,\zeta}$ is the volume of fluid cell $\zeta$ and $n_{p,\zeta}$ is the total number of particles involved in cell $\zeta$. The weight factor $\omega_{i,\zeta}$ is defined as the ratio of the exact volumetric portion of particle $i$ in cell $\zeta$ to the total volume of cell $\zeta$. Clearly, $\omega_{i,\zeta}$ is within $[0, 1]$. If particle $i$ is completely positioned in cell $\zeta$, then $\omega_{i,\zeta} = 1$. 

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The viscous stress tensor can be written in relation to the fluid viscosity $\mu_f$ and velocity $\mathbf{U}_f$ as follows:

$$\tau_f = \mu_f \left[ (\nabla \mathbf{U}_f) + (\nabla \mathbf{U}_f)^T \right]$$ \hspace{1cm} [6.8]

The porosity (or void fraction) of a certain fluid cell is defined as the ratio of the void volume in cell to the total cell volume: $n_f = V_v/V_c = V_o/V_c$ in which $V_v$, $V_o$ are the volumes of the void and particles occupied in cell, respectively; and $V_c$ is the volume of the cell. The porosity in a local cell can be computed on CFDEM based on several valid techniques such as the centre void fraction and divided void fraction methods (Zhao and Shan, 2013). The divided void fraction method calculates the void fraction of a fluid cell by considering the actual portion of particle volume occupied in such a cell where particles overlap the boundary of the fluid cell. As a result it provides a more accurate value of the void fraction in the fluid cell, especially for a dilute and non-uniformly distributed particle system. Therefore, the divided void fraction technique was used in this study.

6.2.2 Fluid-particle interaction forces

In order to account for the effects of fluid on particle motion, the total fluid-particle interaction force $\mathbf{F}_f$ which, in addition to the buoyancy force, can consist of the drag force, pressure gradient force, viscous force, and other unsteady forces (Zhu et al., 2007; Zhou et al., 2010), are introduced into the DEM framework. The drag force acting on particle $i$ positioned in fluid cell $\zeta$, following De Felice’s solution which was used and verified in studies such as Zhou et al. (2010), is calculated using Eq. [6.9] as follows:

$$\mathbf{F}_{d,i} = \frac{1}{8} C_{d,i} \rho_f \pi d_{p,i}^2 n_{f,\zeta}^2 (U_f,\zeta - U_{p,i}) |U_f,\zeta - U_{p,i}| n_{f,\zeta}^{n_p,\psi}$$ \hspace{1cm} [6.9]

where $U_f,\zeta$ and $U_{p,i}$ represent, respectively, the averaged fluid velocity of cell $\zeta$ and velocity of particle $i$ resided in cell $\zeta$; $d_{p,i}$ is the diameter of the particle $i$ in which the drag force acts.
on. $C_{d,i}$ named as the fluid-particle drag coefficient, which is functional to Reynolds number of particle, is estimated by:

$$C_{d,i} = \left( 0.63 + \frac{4.8}{\sqrt{Re_{p,i}}} \right)^2$$ \[6.10\]

where the particle Reynolds number is determined as follows:

$$Re_{p,i} = \frac{n_f \rho_f d_{p,i} |U_f,\zeta - U_{p,i}|}{\mu_f}$$ \[6.11\]

In Eq. [6.9] for the drag force, the porosity function $n_{f,\zeta}^{-\psi}$ considers the presence of other particles in cell $\zeta$ with the power factor $\psi$ functional to Reynolds number $Re_{p,i}$ of particle $i$, thus,

$$\psi = 3.7 - 0.65 \exp \left[ -\frac{(1.5 - \log_{10} Re_{p,i})^2}{2} \right]$$ \[6.12\]

The hydrostatic pressure gradient force accounts for the difference in pressure acting on a particle, and it might consist of the buoyancy force and components generated by the acceleration pressure gradient in the fluid. Zhou et al. (2010) combined these two terms of pressure gradient forces, while some may prefer to the separated force models used in the current CFDEM framework. The pressure gradient and buoyancy forces being exerted on particle $i$ with volume $V_{p,i}$ can be computed individually, as shown below.

$$F_{\nabla p,i} = -(\nabla p)V_{p,i}$$ \[6.13\]

$$F_{bo,i} = -\rho_f g V_{p,i}$$ \[6.14\]

The viscous force generated when a small solid object is moving inside a viscous environment is calculated as follows:
\[ F_{\chi t} = (\nabla \cdot \tau_f) V_{p,i} \]  

[6.15]

Other forces such as the Basset and lift forces were omitted in this study because: (i) the fluid was considered to be laminar and incompressible; (ii) although the motion of fibre particles can have both translational and rotational components, these fluid forces are insignificant compared with other forces such as the drag and pressure gradient forces considered in this study, particularly in laminar flow (Zhu et al., 2007; Zhou et al., 2010). Therefore, the total fluid-particle interaction force acting on particle \( i \) was given by:

\[ F_{f,t} = F_{d,t} + F_{zp,t} + F_{bo,t} + F_{\chi t} \]  

[6.16]

Note that the selection of fluid forces acting on particles represented in this study was applied for fibrous particles under laminar longitudinal flow and without interaction with soil particles. In many cases where the fibres are confined by surrounding soils and geostructures, components of the total fluid-particle interaction force can be different. For instance, viscous force can be ignored when a particle is confined and remains almost static during fluid flow, while the drag force which depends on the difference between \( U_{f,\zeta} \) and \( U_{p,i} \) (Eq. [6.9]) is still considerable. The pressure gradient force is very important when there is a significant drop of pressure through a medium (i.e., low porosity). The drag and pressure gradient forces are usually the major contributors to the total fluid-particle interaction force (O'Sullivan, 2011). On the other hand, when fibre particles have complex motions (e.g., significant rotation under turbulent flow), other fluid forces such as Basset and lift forces will need to be considered.

6.3 Modelling the fibres

Fibres are generally thread-like parts that can be classified as either natural or man-made. Regardless of their origin, their behaviour is generally considered in conjunction with continuum mechanics which treats material as continuous mass rather than discrete particles. Most fibres have a tensile strength that is much higher than bending and shearing, which
explains why fibres can generally be spun (Mishra, 2000). These characteristics make a fibrous structure sensitive to external forces.

Fig. 6.1 Generalized stress-strain and fracture behaviours by DEM-Parallel Bond Model and by experiment on natural fibres (i.e., jute and bamboo)

Modelling a fibre by DEM is discretising a continuous string into a number of individual particles, such that bonding between these particles is applied with respect to the fibre’s main characteristics, as mentioned above. In this study the so-called Parallel Bond Model (PBM) was used to simulate the fibres in DEM. The PBM has been used effectively to simulate a number of materials, including rock (Potyondy and Cundall, 2004), cemented sand (Zeghal and El Shamy, 2008) and geogrids (Ngo et al., 2014), based on elastic stress-strain relations. In addition to tensile, shear and bending behaviours of material that can be captured by the PBM, a review study conducted by Lisjak and Grasselli (2014) also indicated a wide application of the bond model in describing the fracturing process of brittle materials. This indicates a potential of the PBM in simulating a number of fibres, particularly natural fibres such as jute and bamboo, which have mainly linear stress-strain behaviour and brittle fracture (Defoirdt et al., 2010; Biswas et al., 2013). Fig. 6.1 illustrates how a stress-strain curve obtained from DEM using the PBM as summarized by Cho et al. (2007) can match well with
the curve generalized from the experimental results obtained by Biswas et al. (2013) on jute and bamboo fibres.

![Fig. 6.2 Scheme of parallel bond between two spherical particles](image)

As discussed by Potyondy and Cundall (2004), five parameters contribute to the properties of particles bonding, including the normal and shear stiffness per unit area \( k_{bn} \) and \( k_{bs} \); normal and shear strength \( \sigma_b \) and \( \tau_b \); and the bond radius multiplier \( \lambda_b \) which defines a virtual shared area between two particles (Fig. 6.2). The value of \( \lambda_b \) should be ranked from 0 to 1 as noted by O’Sullivan (2011). Generally, the radius of the bond region \( R_b \) between two spherical particles \( i \) with radius \( R_i \) and \( j \) with radius \( R_j \) is estimated based on following condition:

\[
R_b = \lambda_b \min(R_i, R_j)
\]  \[6.17\]

The total force \( F_{b,ij} \) and moment \( M_{b,ij} \) withstood by the parallel bond can be discretised into normal (denoted by sub-script \( n \)) and shear (denoted by sub-script \( s \)) components, as follows:

\[
F_{b,ij} = F_{bn,ij} + F_{bs,ij}
\]  \[6.18\]

\[
M_{b,ij} = M_{bn,ij} + M_{bs,ij}
\]  \[6.19\]
For the initial condition in which the relative displacement and rotation of two particles are zero, the bond force and moment are set to zero. Subjected to relative displacement- and rotation increments, $\Delta D_n, \Delta D_s, \Delta \theta_n, \Delta \theta_s$, the behaviour of particles bonding is governed by the linear elastic equations summarised below.

\[
\Delta F_{bn,ij} = -k_{bn}\Delta D_n A_b \quad [6.20]
\]
\[
\Delta F_{bs,ij} = -k_{bs}\Delta D_s A_b \quad [6.21]
\]
\[
\Delta M_{bn,ij} = k_{bn}J_n\Delta \theta_n \quad [6.22]
\]
\[
\Delta M_{bs,ij} = k_{bs}I_n\Delta \theta_b \quad [6.23]
\]

where $A_b$, $I_b$ and $J_b$ are the area, moment of inertia, and polar moment of inertia of bond cross section, respectively. These parameters are given by:

\[
A_b = \pi R_b^2 \quad [6.24]
\]
\[
I_b = \frac{1}{4}\pi R_b^4 \quad [6.25]
\]
\[
J_b = \frac{1}{2}\pi R_b^4 \quad [6.26]
\]

With respect to beam theory, the maximum normal and shear stresses acting on the bond periphery are computed as follows:

\[
\sigma_{\text{max}} = \frac{-F_{bn,ij}}{A_b} + \left|M_{bs,ij}\right| R_b \quad [6.27]
\]
\[
\tau_{\text{max}} = \frac{|F_{bs,ij}|}{A_b} + \left|M_{bn,ij}\right| J_b R_b \quad [6.28]
\]
The bond is broken if either $\sigma_{\text{max}}$ or $\tau_{\text{max}}$ exceeds its corresponding strength, $\sigma_b$ and $\tau_b$. As a result the bond force and moment acting on the particle are removed.

Fig. 6.3 Behaviour of a single fibre by DEM with different shear stiffness: (a) hard fibre: $k_{bn} = 3 \times 10^9 \text{ Pa/m}$; $k_{bs} = 1 \times 10^9 \text{ Pa/m}$; (b) soft fibre: $k_{bn} = 3 \times 10^9 \text{ Pa/m}$; $k_{bs} = 1 \times 10^2 \text{ Pa/m}$

In order to calibrate the parameters of the parallel bond for a certain material, primary tests such as tension, compression and shear tests are usually required. Because of various properties of fibres including soft fibres such as jute and flax, and hard structural fibres such as coir or others in a man-made group, the calibration process might require more than those tests. The axial compression and shear parameters of many types of fibres can be omitted,
with only the tensile behaviour being considered, whereas the normal stiffness and strength are estimated by tensile testing, while the shear stiffness and strength are used as “dummy” parameters. Note that the determination of these parameters plays an important role in the behaviour of fibres under external forces.

Fig. 6.3 illustrates the behaviour of a single fibre simulated by DEM using the parallel bond with respect to different magnitudes of shear stiffness. In these investigations, the fibres had the same size (0.005 m in diameter and 0.08 m in length), normal stiffness but different shear stiffness. One end of the fibre was fixed while the other end was free to move. Fig. 6.3a demonstrates the response of a hard fibre \((k_{bs} = 1 \times 10^9 \text{ Pa/m and density } \rho_p = 2500 \text{ kg/m}^3)\) subjected to an external force \(F\). The fibre would bend until it reaches a steady state. The fibre having greater shear stiffness is less deformable due to bending. In Fig. 6.3b, behaviour of a soft and light fibre \((k_{bs} = 1 \times 10^2 \text{ Pa/m and density } \rho_p = 1000 \text{ kg/m}^3)\) suspending a mass (with the gravitational force \(F_g\) equivalent to the external force \(F\) applied on hard fibres) at one end is represented. Attributed to the low range of shear stiffness, soft fibres are generally less resistant to shear and bending forces. In fact, the motion shown in Fig. 6.3b is similar to the motion of a simple pendulum system that consists of a string with a heavy mass suspended at one end. An ideal pendulum with a weightless, inextensible and perfectly flexible string (0.08 m in length) fixed at one end has a period of 0.567 s, according to the well-known estimation \(2\pi \sqrt{l/g}\) where \(l\) and \(g\) are the length of string and gravity constant, respectively (Jaiswal and Singh, 2013). This agreed well with the value (0.565 s) predicted by DEM using the PBM to capture the motion of the string. A slight deviation between the two values can be explained by several reasons, particularly: (i) the string in DEM was not weightless and its mass contributed to the motion of the whole system; and (ii) the DEM string was not inextensible.
In addition, the elastic tensile stress-strain relationship governed by the parallel bond of DEM model in LIGGGHTS is seen in Fig. 6.4, which shows a good agreement between LIGGGHTS and PFC-3D used for geogrids (Ngo et al., 2014). Parameters of the PBM used to model geogrids are represented in Table 6.1.

![Tension test for geogrid modelled by LIGGGHTS and PFC-3D](image)

**Fig. 6.4** Tension test for geogrid modelled by LIGGGHTS and PFC-3D

A bundle of fibres can be generated by arranging individual fibres in a certain order. As mentioned in the previous part of this paper, various arrangements of fibres generating
different porous characteristics of the drain system might influence the hydraulic transport of fibres. Within the scope of this study, the validity of CFD-DEM coupling on modelling the hydraulic behaviour of a fibre bundle with respect to fibre-fluid interaction was verified by the uniform triangular and rectangular distributions (Fig. 6.5) of fibres used for computational investigation. The properties of fibre material, including its size, density, and bond parameters were assumed to be uniform for the whole domain. These fibre characteristics were assumed with reference to previous studies (e.g., Mishra (2000)) on fibre engineering, particularly the fibre density ranging from 1000 to 2500 kg/m$^3$ and the equivalent diameters of fibre particles varying from $5 \times 10^{-4}$ to $8 \times 10^{-4}$ m that were used flexibly for different investigations in this study.

![Fig. 6.5 Arrangement of fibres in: (a) rectangular and (b) triangular template](image)

6.4 Correlation between DEM and real fibres

Applying the DEM approach using spherical particles inevitably leads to several limitations in simulating fibre, including, (i) the difficulty in achieving an extremely dense package of fibre, and (ii) the discrepancy between DEM fibre and real fibre shapes that results in a mismatch of hydraulic behaviour and fibre contact. The shape of a single fibre simulated in DEM is a string of discrete spheres that differ from their real shapes because most fibres have continuous and consistent shapes along their axes that enable them to pack densely (Chawla, 2007). However, in the DEM approach using conventional contact models
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(i.e., Hooke and Hertzian models), minimum porosity which was achieved when the fibres were placed parallel and touched each other was 0.476 and 0.425 for rectangular and triangular arrangements, respectively. Note that these limitations of porosity were estimated based on several assumptions that include: (i) treating the fluid cell in macro-scale and considering the fibre in micro-scale; (ii) the fibres consisted of a number of spheres; (iii) fibres were arranged in parallel and touched each other. Discussions regarding the porosity limitation of a fibre bundle can also be found in previous studies such as Tamayol and Bahrami (2009). Moreover, the discontinuity of DEM fibres along their axes caused conflict between the requirements of modelling the fibre contact and porosity. The diameter of spherical particles in DEM can be taken as exactly identical to the cross sectional size of real cylinder fibres to ensure the same contact behaviour in both systems, but it results in a mismatch in their porosity. Therefore this section will focus on solutions addressing these limitations.

6.4.1  Fibre fraction of DEM fibrous system

Due to the different pore structure in DEM and cylinder fibre systems, a quantified relationship between fibres in DEM and those in reality is imperative. Fig. 6.6 illustrates the diameter of real fibres converted to an equivalent diameter of DEM fibres, assuming that the cylinder fibre is a reasonable representation of real fibres. The equivalent diameter of particles in DEM can be estimated with respect to the consistency of porosity in both systems for which the following relationship was obtained.
Fig. 6.6 Correlation of fibre structure in: (a) DEM and (b) reality

\[ d_{DEM}^2 = \frac{3}{2} d_{fr}^2 \] \[ [6.29] \]

where \( d_{DEM} \) and \( d_{fr} \) are the diameters of particles in DEM and cylindrical fibre in reality, respectively. The correlation shown in Eq. [6.29] is to ensure that the porosity of fibres in the DEM simulation is the same as those obtained from real fibres. It is important to note that the porosity plays a key role in solving the Navier-Stokes equation by Finite Volume Method (FVM) that is currently applied to the CFD framework. Strictly speaking, the permeability of a fibre bundle also depends on the pore shape, which differs between the DEM and real fibre systems. Therefore, the impact of pore shape with respect to the KC concept may also be further considered. Particularly a fibre bundle simulated in DEM is actually a spherical arrangement with reference to a hydraulic diameter \( d_h = 4/d_{DEM} \), while a cylindrical fibre bundle corresponds to \( d_h = 6/d_{fr} \). The theoretical application of the KC equation for spherical and cylindrical porous systems can be represented by Eq. [6.30] and Eq. [6.31], respectively.
where the sub-scripts \( s \) and \( c \) refer to the spherical and cylindrical systems, respectively. For the same magnitude of porosity, the following relationship between the permeability of spherical and cylindrical porous mediums can be obtained.

\[
\frac{K_s}{K_c} = \frac{2 k_{s,c}}{3 k_{s,s}}
\]  

[6.32]

Eq. [6.32] explains the linkage between the permeability of spherical and cylindrical fibrous systems with respect to the KC approach. \( K_s \) is the permeability obtained from the numerical model using spherical particles, and \( K_c \) of cylindrical element system can then be estimated based on the value of \( K_s \) according to Eq. [6.32]

6.4.2 Modified contact model for fibre simulation by DEM

Given the differences between the characteristics of DEM and real fibres mentioned above, the concept of the conventional contact model must be modified to enable DEM fibres to attain a lower porosity and match the real fibre contact. Attributed to the overlap concept for soft particles proposed by Cundall and Strack (1979), the conventional contact model, including the linear Hooke and non-linear Hertzian models can be modified to achieve a higher fibre fraction. In DEM, the conventional contact model (Fig. 6.7a) will generate a positive interaction force between two particles whenever they overlap; and this prevents it from creating a lower porosity than the limited values mentioned above. The contact force \( F_{c,ij} \) between the particles \( i \) and \( j \) is generally controlled according to the following spring-dashpot model (Bertrand et al., 2005).
\[ F_{c,ij} = F_{cn,ij} + F_{cs,ij} \]  \[ F_{cn,ij} = k_{cn} D_{c,ij} - \gamma_{cn} U_{cn,ij} \]  \[ F_{cs,ij} = k_{cs} s_{ij} - \gamma_{cs} U_{cs,ij} \]

In the above, the subscripts \( n \) and \( s \) indicate the normal and shear components, respectively. \( F_c, D_c, s, k, \gamma \) and \( \nu \) are respectively the force, overlap, tangential displacement, stiffness, viscoelastic damping factor and relative velocity, with \( i, j \) being referred to two particles in contact. The force components \( F_{cn,ij} \) and \( F_{cs,ij} \) are activated when the distance between particles \( i \) and \( j \), \( D_{c,ij} < (R_{fDEM,i} + R_{fDEM,j}) \).
diameter $d_{fr}$, while the diameter of DEM particles $d_{fDEM}$ was used to compute the porosity of the system. The contact force in the current model was hence generated when $D_{c,ij} < (R_{fr,i} + R_{fr,j})$ instead of $(R_{fDEM,i} + R_{fDEM,j})$ in the conventional contact model, which enabled the DEM spherical fibres to be closer to each other, and thus achieve a higher fibre fraction. With respect to the modified contact model, the minimum porosity could reach significantly lower values than those (i.e., 0.476 and 0.425 for rectangular and triangular fibre arrangements, respectively) based on the conventional contact models.

6.5 Simulation of fluid flow through fibrous material

In this section, details of the coupled CFD-DEM technique used to model the hydrodynamic behaviour of fibrous material are presented. To verify this technique, the fibres with immobilisation of one ends were created. Significant motion of fibres might cause variation of fibre arrangement, and as a result the hydraulic conductivity of the system is unstable and incomparable to other studies which usually consider fibres to be static during fluid flow. Besides, in this study, the dimensionless permeability of a fibre bundle was investigated with respect to several assumptions, including (i) the fibres were distributed uniformly; (ii) all the individual fibres in the bundle were homogeneous, and (iii) fluid flow was laminar. It is widely accepted that given an ordered array of fibres, the axial flow of fluid through a fibre bundle is independent of the size and shape of its cross-section (Endruweit et al., 2013). Therefore, to simplify, a cubic fluid domain with quadratic meshing was used with respect to the following desired targets: (i) porosity of the system; (ii) characteristics of fibre arrangement, and (iii) consistent CFD mesh and flow length. A typical fibre bundle modelled by DEM with reference to fluid flow can be seen in Fig. 6.8. The porosity of this system was subjected to change from 0.2 to 0.95 in this study, which corresponded to loose, medium, and dense fibre packing.
Fluid behaviour was managed by FVM based OpenFoam software which solves the governing equations of fluid in the control cells of CFD locally, therefore fluid domain discretisation plays a key role in the consistency and stability of numerical computations. With respect to the variation of porosity, the meshing fluid domain should be carried out while considering the porosity in each CFD cell and noting the correlation between the size of fluid cells and particles. Note that the current CFD-DEM coupling is based on the treatment that the fluid domain is evaluated in macroscopic variation while the particles are considered in microscopic variation. This means the dimensions of the CFD cell must be large compared to the size of the particles (Zeghal and El Shamy, 2008). A wide range of studies used various size ratios of fluid cell to particle diameter, particularly from 1 to 5 (Chen et al., 2011; Smuts et al., 2012; Zhao and Shan, 2013; Shan and Zhao, 2014), whereas
in this study a set of ratios between the CFD cell and particle diameter from 1 to 5 were also found to be suitable for numerical computation.

One of the most important factors contributing to the stability and accuracy of the numerical process is time discretisation, because a finer time frame guarantees a higher stability and accuracy of simulation but costs more in terms of computational time. The time step of a DEM framework was generally selected with reference to two critical values, $\Delta t_h$ and $\Delta t_r$ following the Hertzian and Rayleigh conditions (Li et al., 2005; Kloss et al., 2012) described by Eq. [6.36] and [6.37], respectively.

$$\Delta t_h = 2.87 \left( \frac{m_i^2}{R_e Y_e^2 U_{p,\text{max}}} \right)^{0.2}$$  \[6.36\]

$$\Delta t_r = \frac{\pi R}{(0.1631 \times \nu + 0.8766) \sqrt{\rho_p / G}}$$  \[6.37\]

In the above, $R$ is the average radius of particles; $\nu$ is Poisson’s ratio; $\rho_p$ denotes the density, and $G$ is the shear modulus of the particle. $U_{p,\text{max}}$ is the maximum relative velocity of particles. $R_e$, $Y_e$ and $m_e$ are the effective radius, Young’s modulus, and mass of particles $i$ and $j$ in contact, respectively.

$$\frac{1}{R_e} = \frac{1}{R_i} + \frac{1}{R_j}$$  \[6.38\]

$$\frac{1}{Y_e} = \frac{1 - \nu_i^2}{Y_i} + \frac{1 - \nu_j^2}{Y_j}$$  \[6.39\]

$$\frac{1}{m_e} = \frac{1}{m_i} + \frac{1}{m_j}$$  \[6.40\]

While the time step of DEM framework $\Delta t_p$ was considered with respect to the critical
time steps $\Delta t_h$ and $\Delta t_r$, the time step of CFD was determined in conjunction with the Courant number (OpenFOAM, 2014) which is defined below.

$$Co = \frac{\Delta t_f |U_f|}{\Delta x}$$  \[6.41\]

where $\Delta t_f$ is the time step of numerical approximation in CFD; $U_f$ is the magnitude of fluid velocity through the cell, and $\Delta x$ is the size of the cell in the direction of fluid flow. The factor $Co$ should be less than unity for every cell of the fluid domain, which means the critical value of time step in the fluid solver can be written below as:

$$\Delta t_f < \Delta t_{f\_crit} = \frac{\Delta x}{|U_f|}$$  \[6.42\]

In CFD-DEM coupling, the time interval to exchange information between two phases is a crucial criterion to ensure the stability and accuracy of the simulation. The closer exchange and update between continuum (CFD) and discrete (DEM) platforms results in higher accuracy, but it is more costly in terms of computational time, whereas information on the solid phase such as motion and velocity might be lost or updated incorrectly in the CFD framework if the time interval is not small enough. The size of the time interval depends mainly on the nature of the problem simulated and might range over a wide scale, for example from 10 (Goniva et al., 2010) to 1000 (Zhao and Shan, 2013). In this study, considering the properties of fibres and the CFD meshing details mentioned above, time steps of $10^{-7}$ s and $10^{-5}$ s were used for the DEM and CFD frameworks, respectively. The fluid-particle interaction was routine in every 100 DEM time steps $\Delta t_p$.

Fluid flow was set from one side of the flow path to the other, through fibrous media. The flow velocity was as small as possible to ensure proper laminar flow behaviour (Trussell and Chang, 1999), and one ends of the fibres were fixed. To ensure the fully developed
condition of flow, the fibre bundle should be long enough, i.e., \( L/d_f > 40 \) (Tamayol and Bahrami, 2010) where \( L \) is the length of fibre bundle. In addition, extended flow paths before and after fibre domain were included (Fig. 6.8b), and the walls of CFD domain were assigned as slip boundaries to guarantee no friction of flow and uniform distribution of velocity. The drop in pressure could be extracted from the results of numerical computation, and Darcy’s law which describes the permeability of porous media relative to the flow velocity and drop in pressure was used to calculate the longitudinal permeability of fibrous material.

\[
U_{f,s} = \frac{K}{\mu_f} \nabla p
\]  

[6.43]

where \( U_{f,s} \) and \( \mu_f \) are the superficial velocity and the dynamic viscosity of fluid, respectively; \( \nabla p \) is the pressure gradient accounting for the pressure drop \( \Delta p \) over the length of flow path; and \( K \) is the permeability. The dimensionless permeability \( K/d_f^2 \) can then be calculated based on the \( U_{f,s} \) and \( \nabla p \) obtained from the numerical simulation.

6.6 Results and discussion

6.6.1 Hydraulic conductivity

To verify the current numerical technique with conventional methods which consider fibres to be static during fluid flow, the DEM fibres with high bond stiffness were used (i.e., \( k_{bn} = 1 \times 10^{11} \text{ Pa/m} \) and \( k_{bs} = 1 \times 10^9 \text{ Pa/m} \)). Fig. 6.9 shows the variation of fluid fields, including the velocity and pressure, when flowing along fibre bundle with a porosity of 0.47. In this series of studies, a superficial velocity \( U_{f,s} = 0.001 \text{ m/s} \) was used to ensure fluid flow in the Darcy regime. The relationship between superficial and duct velocities (\( U_{f,s} \) and \( U_{f,d} \), respectively) is described as \( U_{f,s} = n_f U_{f,d} \), and shown in Fig. 6.9.
Fig. 6.9 Average velocity, porosity and pressure drop through fibrous drain

The CFD framework based on FVM that was used to solve the averaged Navier-Stokes equation locally in the individual fluid cell was able to describe the distribution of fluid velocity for varying arrangements of fibres, as discussed by Tamayol and Bahrami (2008) using static fibres. Fig. 6.10 represents the velocity distributions of fluid flow through the triangular and square arrangements of fibres modelled by the CFD-DEM coupling technique, and indicates its ability to capture the variation of fluid velocity due to the fibres being re-arranged. The motion of fibrous particles due to external force causes variations of porosity in the fluid cell, and as a result, the fluid fields changes by solving the Navier-Stokes equation. A finer mesh of CFD means a larger number of fluid cells generated and that can provide a more accurate description of fluid velocity distribution, but note that the current technique considers the CFD cell in a macro scale unlike the micro dimension of the DEM particles. This approach (coarse-grid approximation method, Tsuji et al. (1993)) cannot describe the flow within each individual fluid cell of the porous system (O'Sullivan, 2011), as a result, limits the simulation to capture velocity distribution effectively, particularly for the
Chapter 06  Parallel Fibres-A Numerical Treatment

densely packed fibres where the porosity is more homogeneous. It is evident that a uniform porosity in all fluid cells gives tangible outcomes after the locally averaged Navier-Stokes equation is solved, regardless of how the fibres are arranged. Therefore, in this study the velocity of the fluid in a dense fibre bundle could be considered uniform in all the fluid cells.

![Fibres](image)

**Fig. 6.10** Velocity ($U_f$) distribution of fluid flow through: (a) squarely and (b) triangularly arranged fibres

Fig. 6.11 represents the dimensionless longitudinal permeability of the squarely arranged fibres obtained from the CFD-DEM coupling technique; it shows a good agreement with those gained from Kozeny-Carman solution and other studies, including the experimental works by Sullivan (1942); the numerical simulation by Tamayol and Bahrami (2008); and the analytical solutions by Happel (1959) and by Tamayol and Bahrami (2009). Note that in this investigation the fibres had insignificant motion and pressure was shared by the solid and fluid phases in the system, while other conventional studies used completely static fibres. The results show a good match between the coupled CFD-DEM technique and other analytical and numerical simulations for medium and loose fibre fraction ($0.4 < n_f < 0.95$), but there is a relative deviation when the porosity is less than 0.4. All the analytical and numerical methods presented agree with the experimental work of Sullivan (1942) within the porosity of very loose fibre bundle ($n_f > 0.9$) and only begin to deviate from this experimental trend when $n_f < 0.9$. The Happel (1959) and KC analytical methods, which do not consider the
velocity distribution of fluid flow, share the same trend of permeability, while other studies (Tamayol and Bahrami, 2008, 2009) report higher values of hydraulic conductivity when the porosity is less than 0.4. For densely packed fibres where the current CFD-DEM coupling approach is not effective to capture the velocity distribution, the permeability curve by CFDEM is as close as KC and Hapel (1959) which assumes a uniform velocity distribution of fluid flow.

Fig. 6.11 Dimensionless permeability of squarely arranged fibres over porosity by CFDEM with uniform distribution of fluid velocity and in comparison with other studies

An investigation into the hydraulic conductivity of a fibrous medium in relation to the fibre arrangements including the rectangular and triangular distributions of fibres was conducted by CFD-DEM coupling. Given a parallel fibrous bundle with a uniform porosity, the results indicated that the longitudinal permeability of such a system slightly depended on the template of fibre distribution. Fig. 6.12 which represents a typical result obtained from the CFD-DEM coupling technique for rectangular fibre distribution, shows an insignificant variation of the hydraulic conductivity against the arrangement ratio $S_y/S_x$ of a fibrous system with $S_x$ and $S_y$ are the fibre distances in $x$ and $y$ directions (Fig. 6.5). This is reasonable
because for unidirectional flow with a slippery velocity boundary condition and a uniform
distribution of fluid velocity, flow parallel to the fibres can be treated as flow through a group
of capillaries that is mainly related to the total cross section area of pores (Carman, 1937;
Tamayol and Bahrami, 2009).

![Graph](image)

Fig. 6.12 Dimensionless longitudinal permeability against arrangement ratio $S_y/S_x$

6.6.2 Fluid-particle interaction forces

Particles forming fibres are subjected to a number of forces which determine the
motion of the whole fibre during fluid flow (Fig. 6.13a). For upward laminar fluid flow along
the fibres in this study, the static buoyancy force and other fluid interaction forces acting on a
fibre particle were in the same direction, and given the parallel arrangement of fibres, the
contact force of fibre particles could be negligible. A study on the relationship between the
total fluid-particle interaction force and flow velocity was carried out by CFD-DEM coupling
with the uniform equivalent particle diameter, $d_{DEM} = 8.10^{-4}$ m and the porosity of the system
$n_f = 0.665$. Note that subjected to a uniform distribution of particles and slippery boundary,
the total fluid-particle interaction force was identical to all the particles in the system.
Fig. 6.13 Forces acting on a fibre particle under longitudinal fluid flow: (a) potential forces acting on a fibre particle; (b) variation of forces subjected to increasing fluid velocity

To evaluate the correlation between the inertial and viscous components of flow through a particulate media, the Reynolds number is useful according to Eq. [6.10]. Fig. 6.13b represents the total fluid-particle interaction force $F_f$ acting on a fibre particle of the uniform porosity system in relation to different magnitudes of the superficial fluid velocity along the fibres. For a range of fluid velocities of less than 0.0013 m/s corresponding to the Reynolds number lower than its unity (Darcy regime), the flow in this regime is not only laminar but also “creeping” flow (Trussell and Chang, 1999), which have insignificant inertial contribution and a major component of the static buoyancy force. For a higher range of Reynolds number (Forcheimer regime), an increasing influence of inertial part on the total fluid-particle interaction force can be observed in the Fig. 6.13b. Besides, a gradual increase of the total fluid-particle interaction force occurs in a range of flow velocities of less than 0.01 m/s before there is a sharp acceleration of such force due to a greater range of flow velocity. This increasing trend of the total fluid-particle interaction force also indicates a bigger role of the drag force in the total fluid force acting on the fibre particle when the fluid...
velocity progresses. Additionally, Fig. 6.13b shows the correlation between the total fluid-particle interaction force and fibre density which ranged from 1000 to 2500 kg/m$^3$. In this study the total fluid-particle interaction force was influenced slightly by the density of the fibre, but for different characteristics of fibres and fluid flow, the fluid interaction force acting on the fibre particles would be more heavily dependent on the density of fibres. Therefore the behaviour of fibres due to fluid flow must be considered in conjunction with their density and bond stiffness.

6.6.3 Motion of fibres under fluid flow

In order to observe the influence of fluid flow on the behaviour of fibre particles, one ends of fibres were fixed, while the other ends were free to move. A laminar (longitudinal) flow through a parallel fibre bundle with a range of density from 1000 to 2500 kg/m$^3$ and an equivalent diameter of the fibre particle, $d_{DEM} = 8.10^{-4}$ m was created in this section. In addition to the contact force which could be ignored in this investigation as explained in the previous section, the external forces acting on fibre particles included the fluid-particle interaction and gravitational forces (Fig. 6.13a). All fibres in the bundle were assigned the same set of characteristics and under a uniform fluid-particle interaction force that caused the fibres to act in an identical way. Motion of fibre particles with various values of the normal stiffness, $k_{bn}$ of the parallel bond and different magnitudes of fibre density was subjected to investigate in conjunction with different levels of flow velocity.

The axial strain of fibre that was considered as the ratio of the longitudinal displacement of the freely moving end to the total initial length of fibre is shown in the Fig. 6.14 in relation to the superficial velocity of flow. A higher velocity of laminar flow brings a bigger fluid interaction force exerting on the particles in the system, and that results in a more displacement of the fibre particles. The density of fibre shows a considerable impact on motion of the fibre particles in a range of flow velocities lower than 0.08 m/s, where the total
fluid-particle interaction force is insignificant compared to the gravitational force. For a higher magnitude of flow velocity in which, the force generated by fluid flow acting on the fibre particles is dominant, the axial strain of fibre becomes less dependent on the density of fibre. Given a laminar flow, the computational results indicated that the longitudinal motion of fibre particles could be negligible for the fibres with a normal stiffness $k_{bn}$ of bond greater than $10^6$ Pa/m (less than 1% of axial strain). Thereby, the motion of fibres must be evaluated in association with the stiffness of particles bonding.

![Graph showing axial strain of fibre under longitudinal flow in relation to superficial flow velocity](image)

**Fig. 6.14** Axial strain of fibre under longitudinal flow in relation to superficial flow velocity

### 6.7 Model Limitations

The study has a number of limitations. First, the parallel bond model might not accurately simulate the fibres which have predominantly ductile fracture. Improving the particle bonding would enable the coupling technique to be valid in a wider range of fibres. In addition, the modified contact model used to generate dense fibre packing cannot alter the fact that the DEM fibres were actually a series of spherical particles which were generally different from the real shape of fibres. Moreover, uniform fibre arrangement used in this
study was a simple case to demonstrate the technique. Application of the method to real drainages which have predominantly disordered arrangement of fibres would be important. Finally, the hydraulic behaviour of fibrous media was investigated in the absence of soil particles and only fluid-fibre interaction was considered. While in many cases the hydraulic behaviour of fibrous geomaterials is inherent in the assembly of particles, rigorous experimental works such as filtration test are needed to further validate the coupling technique used in this study.

6.8 Conclusions

This paper describes and discusses a technique for numerically simulating the hydraulic behaviour of fibrous materials with respect to interaction between the fluid and solid phases. Fibre elements were simulated by the discrete element method while the fluid behaviour was captured by the finite volume method simultaneously. The following conclusions could be drawn:

6.8.1 Fibrous geomaterials, particularly natural fibres such as jute and bamboo which have mainly linear stress-strain relationship and brittle fracture, can be simulated by the parallel bond model of a DEM framework. By adopting different sets of parameters for bonding, $k_{bn}$ and $k_{bs}$, various behaviours including soft to hard fibres could be modelled.

6.8.2 A coupled CFD-DEM technique can be applied to describe the hydraulic behaviour of fluid flow through a fibrous medium with respect to the interaction between fluid-solid phases. For the case that fibres had insignificant motion, the longitudinal permeability obtained from CFD-DEM coupling technique was matched well compared to the conventional methods which considered fibres to be completely static during fluid flow. The hydraulic conductivity of fibrous materials modelled by the CFD-DEM technique, particularly for the medium and loose fibre bundle ($0.4 < n_f <$
1), agreed well with those obtained from other analytical and numerical studies in past literature, although there was a significant deviation in the hydraulic conductivity for the lower range of porosity \( n_f < 0.4 \), where various distributions of fluid velocity were considered in recent studies. Moreover, with respect to the uniform distribution of velocity, the longitudinal permeability of the parallel fibre bundle was barely dependent on the arrangement ratio \( S_y/S_x \).

6.8.3 The study also indicated that the coupling technique can describe the behaviour of fibre elements under fluid flow. The total fluid-particle interaction force was found to be heavily dependent on the flow velocity in a range of velocity greater than 0.01 m/s. Subjected to laminar longitudinal flow, the axial strain of fibres was found to be considerable when the normal stiffness of bond \( k_{bn} \) was lower than \( 10^6 \) Pa/m. The coupled CFD-DEM technique showed a reasonable dependence of the dynamic behaviour of fibre particles on fibre characteristics, including the density and the bond attributes while fluid flowing.

6.8.4 The modified contact model applied in this study enabled the coupling technique to simulate the hydraulic conductivity of fibre systems with a low range of porosity (i.e., 0.2). This kind of treatment allowed the spherical particles in DEM to be placed closer to each other without generating an interaction force to achieve a fibre bundle with a higher density.

6.9 Acknowledgements

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Chapter 7 EXPERIMENTAL AND NUMERICAL INVESTIGATIONS INTO HYDRAULIC BEHAVIOUR OF COIR FIBRE DRAIN

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7.1 Introduction

Natural fibres drains which are emerging as environmentally-friendly alternative to the conventional geosynthetic materials have received increasing attention in the recent years, including their application as prefabricated vertical drains (PVD) in soft soil consolidation for infrastructure development (Lee et al., 1994; Venkatappa Rao et al., 2000; Kim and Cho, 2008). As the process of biodegradation of these natural materials takes several years (i.e. after serving the period of primary consolidation), PVDs made from jute and coir are now becoming increasingly popular, and manufactured for worldwide export in South and Southeast Asian countries. Most applications where naturally occurring materials are used for either filtration or drainage in geotechnical practice are based on their favourable hydraulic conductivity (Jang et al., 2001; Asha and Mandal, 2012). Consequently, there is a need for creating a computational scheme which can predict the hydraulic behaviour of these fibrous media accurately. Nguyen and Indraratna (2016) used a combined approach between the Discrete Element Method (DEM) and Computer Fluid Dynamics (CFD) to model fibrous geomaterials, and found a good agreement between this solution and previous studies in relation to fluid flow characteristics. Although this study verified the CFD-DEM technique by only applying it to predict the permeability of an idealised arrangement of parallel fibres, it provided a launching pad to extend the numerical approach further to encompass real
natural fibres that have a more complex porous structure (e.g., twisted fabric).

Many previous studies clarified the hydraulic behaviour of natural fibres on a macro scale; for instance, Venkatappa Rao et al. (2000), and Asha and Mandal (2012) studied the discharge capacity of jute drains, while Asha et al. (2012) studied the transverse permeability of jute geotextiles. However, there is a distinct lack of studies focused on micro characteristics of porous media that could provide a better insight into the hydraulic behaviour of natural fibre drains. Since the permeability of porous materials depends on the size and arrangement of fibres (Ozgumus et al., 2014), variations in the micro-structure of fibrous media can significantly change the hydraulic conductivity of the whole drain system and therefore the overarching objective of this study.

The Kozeny-Carman (KC) method is usually preferred in practice due to its computational convenience. Previous studies (Sullivan, 1942; Gutowski et al., 1987; Gebart, 1992) have shown that the KC concept is also applied for longitudinal flow through fibrous media, where the relationship between permeability and the porosity is given by:

$$K = \frac{d_f^2 n^3}{16k_k(1-n_f)^2} \quad [7.1]$$

where $d_f$ is the average diameter of fibres in the drain, $n_f$ is the porosity (or void fraction) of the medium, and $k_k$ is the Kozeny constant that is usually determined by experimental methods. This empirical constant has a wide range of values that depend on the porous characteristics of media, as summarised by Ozgumus et al. (2014), which is why specifying $k_k$ for practical applications is still being debated.

This study focuses on the hydraulic behaviour of coir (coconut) fibre, because it is one of the most commonly used natural fibres worldwide. Primary tests such as tension and bending were carried out on coir fibre to determine its basic mechanical properties, and an experimental scheme to determine the hydraulic conductivity of the coir bundles with
different porous features was then carried out. The experimental results were then used to validate the CFD-DEM technique and also compared with the conventional KC analytical approach.

### 7.2 Experimental investigation on the longitudinal permeability of coir fibres

#### 7.2.1 Fibrous drains

A natural fibre drain is a combination of single fibres in a certain arrangement that enables fluid to flow through its porous medium. There are currently a variety of fibre drains made from natural fibres such as jute, coir, and straw with either circular or band shaped cross-sections. Of these, coir and jute are the most preferable due to their abundance in developing nations in South and Southeast Asia. Coir fibre consists of approximately 40-45% lignin and 35-45% cellulose components (Gupta, 2011) that make this fibre more robust and durable than jute which only has around 12% lignin (Som et al., 2009). In this study, dry brown coir fibres provided by the National Jute Board of India (NJBI) were used to generate fibre drains which were then subjected to an experimental investigation into their hydraulic behaviour. Physical properties of the coir fibres which were obtained by carrying out laboratory tests (represented in the following parts of this paper) are summarized in Table 7.1. Note that to minimize the influence that the water absorption of coir fibres could have on the hydraulic test, coir fibre drains were soaked in water to make them saturated before testing.

<table>
<thead>
<tr>
<th>Density (kg/m$^3$)</th>
<th>Water content (%)</th>
<th>Tensile strength (MPa)</th>
<th>Elastic Modulus (GPa)</th>
<th>Diameter (mm)</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry</td>
<td>Saturated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1160</td>
<td>14</td>
<td>94</td>
<td>188 ± 34</td>
<td>4.2</td>
<td>0.102- 0.495</td>
</tr>
</tbody>
</table>

Table 7.1 Physical properties of brown coir fibres
Straight and undamaged coir fibres were used to create fibre drains, of which two types of fibre structure were investigated, non-twisted and twisted bundles. The non-twisted bundles consisted of individual coir fibres arranged almost in parallel (no twisting) whereas in the twisted structure, single fibres were packed together and twisted around the longitudinal axis of the bundle to a certain degree (Fig. 7.1a); fundamentally, the tighter the fibres were twisted together, the denser and stronger their composition. The fibre fraction was approximately manipulated by the number of single fibres in the bundle, such that as more fibres are packed, the denser the bundle generated. Fig. 7.1b and Fig. 7.1c show how non-twisted and twisted bundles can be generated using coir fibres, respectively.

Fig. 7.1 Fibre drains composed of coir fibres under optical microscope: (a) schematic details of twisted fibre bundle; (b) non-twisted fibres; and (c) twisted fibres
7.2.2 Experiment to determine the hydraulic conductivity of a fibre drain

Experimental methods with unidirectional and radial flow are the two common approaches used to determine the hydraulic conductivity of fibrous materials (Sharma and Siginer, 2010). Fibres are pre-formed in a mould before being subjected to fluid flow, and low injection pressure is required to ensure the fibres remain in a static condition. Either the fluid velocity or pressure is controlled while the fluid is flowing. In this study, an experimental process based on the pressure controlled model was designed and established (Fig. 7.2a).

![Diagram of experiment model](image)

**Fig. 7.2** Experiment model to determine hydraulic conductivity of fibrous drain: (a) schematics of experiment model; (b) fibre tube; (c) cross-section of fibre tube after casting
The bundles of fibre which had an identical cross sectional area and length were placed inside 4 mm diameter by 100 m long hard tubes (Fig. 7.2b and Fig. 7.2c). The interior surface of the tube was smooth to reduce the effect of friction on fluid flow. The inlet of the tube was connected to a constant head water tank with adjustable elevation to generate water flow under different static pressures, and manometers were installed to measure the water heads at the inlet and outlet of the tube. Water from the inlet drained through the fibrous environment was collected at the outlet of the tube, so that the hydraulic gradient of the flow could be obtained with respect to the length and the difference in water heads between the inlet and outlet of the bundle. The volume of water discharged through the fibrous system over time was recorded. The viscosity of the water was determined according to its temperature measured, in accordance with ASTM D4716 (ASTM D4716, 2008). The dynamic viscosity of the water used in this study was 1.004x10^{-3} Pa.s at 20°C.

To obtain the porous characteristics of this fibrous system, a series of micro-analyses were carried out in the following manner: after the hydraulic test, the tube containing fibres was dried by blowing warm dry air through the tube, which was then immersed into a mixture of resin and hardener to maintain the structure of the fibrous medium. These samples were then subjected to a stacking technique along the fibres in which a series of photos of the cross-section of the bundle were taken along the longitudinal axis of samples with an optical microscope. Image analysis techniques that are available in the ImageJ software (Rasband, 2014) were carried out on these photos to obtain geometrical information such as the cross sectional area and the coordinates of individual fibres in a given drain to enable the fibrous system to be reconstructed on the DEM framework. Fig. 7.3a shows an example of cross-sections of coir fibres under microscopic observation. The coir fibres have almost round cross-sections that are reasonable to be modelled by spherical particles which are commonly used in DEM.
Fig. 7.3 Physical properties of coconut coir fibres: (a) cross-section of the fibres under microscope observation; (b) size distribution of fibres in a bundle

Fig. 7.3b shows how the diameters of the coir fibres are distributed within a typical drain with the most common sizes being from 150 to 300 µm, and which accounted for more than 70% of the total number of fibres. The average diameter of the coir in this study was approximately 236 µm, which is within the common range of this fibre (100 to 530 µm), as
summarized by Ali (2010). The density of the fibre investigated in this study was 1160 kg/m$^3$ that corroborates with those reported by other studies (Rao and Rao, 2007; Defoirdt et al., 2010). The water content of the fibre (Table 7.1) was determined as the ratio of the mass of water in the fibre to the mass of dried fibre.

On the basis of the discharge volume $V_w$ recorded at the outlet of the fibre tube over time $t$, the hydraulic conductivity $k$ was estimated as follows:

$$k = \frac{V_w R}{i A t}$$

[7.2]

where $R_t$ is the correction factor for the viscosity of water, depending on the water temperature (ASTM D4716, 2008); $A_t$ is the internal cross sectional area of the tube and $i$ is the hydraulic gradient. Note that in this experiment, fluid flow was investigated under a small difference in water heads to ensure laminar flow, while the discharge volume $V_w$ was measured at a steady state of flow.

7.3 Numerical modelling of hydraulic behaviour of fibrous material

In the present approach, fibre particles are simulated by implementing the Discrete Element Method (DEM) code onto an open source framework called LIGGGHTS (Kloss and Goniva, 2010), while fluid behaviour is described by the Computational Fluid Dynamics (CFD). Interaction between the fluid-solid phases is carried out by a mutual platform called CFDEM (Goniva et al., 2010) which exchanges and updates information between each phase. The behaviour of particles and fluid is described on the basis of the following concepts.

7.3.1 Fluid behaviour

This study assumed an incompressible fluid with conservation of mass where the fluid variables, including the velocity $U_f$ and pressure $p$ are governed in individual cells as represented by the following Navier-Stokes equations.
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\[ \frac{\partial n_f}{\partial t} + \nabla \cdot (n_f U_f) = 0 \]  

[7.3]

\[ \frac{\partial (\rho_f n_f U_f)}{\partial t} + \nabla \cdot (\rho_f n_f U_f U_f) = -n_f \nabla p - \mathbf{f}_p + \nabla \cdot (n_f \tau_f) + n_f \rho_f \mathbf{g} \]  

[7.4]

In the above equations \( \tau_f \) denotes the viscous stress tensor while \( \rho_f \) is the fluid density while. The porosity \( n_f \) of a certain fluid cell is defined as the ratio of the void volume in a cell to its total volume: \( n_f = V_v/V_c = 1 - V_p/V_c \) where \( V_v, V_p \) are the volumes of the void and particles occupied in a cell, respectively; and \( V_c \) is the volume of the cell. \( \mathbf{f}_p \) is the mean volumetric particle-fluid interaction force representing the effect of the solid phase on the fluid phase within the cell. By considering that the fluid cell \( \zeta \) contains \( n_p \) particles, \( \mathbf{f}_p \) of cell \( \zeta \) can be estimated by Eq. [7.5] as follows:

\[ \mathbf{f}_{p,\zeta} = \sum_{i=1}^{n_{p,\zeta}} \omega_{i,\zeta} \left( \frac{F_{p_i}}{V_{c,\zeta}} \right) \]  

[7.5]

where \( F_{p,i} \) is the total force acting on particle \( i \); \( V_{c,\zeta} \) is the volume of the fluid cell \( \zeta \). The factor \( \omega_{i,\zeta} \) representing the volumetric portion of particle \( i \) residing in cell \( \zeta \) is estimated as the ratio of the exact volumetric portion of particle \( i \) in cell \( \zeta \) to the total volume of cell \( \zeta \).

The viscous stress tensor \( \tau_f \) can be written in relation to the fluid viscosity \( \mu_f \) and velocity \( U_f \) as follows:

\[ \tau_f = \mu_f \left[ (\nabla U_f) + (\nabla U_f)^T \right] \]  

[7.6]

7.3.2 Particle behaviour

The motion of particle \( i \) in DEM, including the rotational and translational components, is governed by the following equations:
where $U_{p,i}$ and $\Omega_{p,i}$ are the translational and angular velocities of particle $i$, respectively; $m_i$ is the mass and $I_i$ is referred to as the inertia moment of particle $i$; $F_{c,ij}$ and $M_{c,ij}$ are the contact force and torque acting on particle $i$ by particle $j$ (or walls), while $n^c_i$ is the number of total contacts of particle $i$. $F_{g,i}$ is referred to as the gravitational force, while $F_{f,i}$ is the total fluid-particle interaction force imported from the fluid domain acting on particle $i$.

The total fluid-particle interaction force $F_{f,i}$ which accounts for the effect of fluid on particle motion, can consist of the drag force, the pressure gradient force, the viscous force, and other unsteady forces such as the virtual mass, the Basset and the lift forces (Zhu et al., 2007; Zhou et al., 2010). Previous studies (Zhu et al., 2007; Zhou et al., 2010) have shown that any unsteady forces are usually insignificant compared to the drag and pressure gradient forces, especially in laminar flow. Assuming laminar flow in this study, the unsteady forces were ignored.

The drag force acting on particle $i$ positioning in fluid cell $\zeta$, according to De Felice’s solution which was used and verified by Zhou et al. (2010), is given by:

$$F_{d,i} = \frac{1}{8} C_{d,i} \rho_f \pi d_{p,i}^2 n_{f,\zeta}^2 (U_{f,\zeta} - U_{p,i}) |U_{f,\zeta} - U_{p,i}| n_{f,\zeta}^{-\nu}$$

where $U_{f,\zeta}$ and $U_{p,i}$ are referred to as the averaged velocity of fluid in cell $\zeta$ and the velocity of particle $i$ residing in cell $\zeta$, respectively; $D_{p,i}$ is the diameter of particle $i$ where the drag force acts on, and $C_{d,i}$ is the fluid-particle drag coefficient which is calculated by:
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\[ C_{d,i} = \left( 0.63 + \frac{4.8}{\sqrt{R_{e_{p,i}}} \right)^2 ] \tag{7.10} \]

where \( R_{e_{p,i}} \) is the particle Reynolds number which is determined by:

\[ R_{e_{p,i}} = \frac{n_f \rho_{f} d_{p,i} |U_{f,\zeta} - U_{p,i}|}{\mu_{f}} \tag{7.11} \]

In Eq. [7.9] the porosity function \( n_{f,\zeta}^{-\psi} \) represents the presence of other particles in cell \( \zeta \) in relation to the power factor which is a function of the Reynolds number \( R_{e_{p,i}} \) and is estimated by:

\[ \psi = 3.7 - 0.65 \exp \left[ - \frac{1.5 - \log_{10} R_{e_{p,i}})^2}{2} \right] \tag{7.12} \]

Note that according to Eq. [7.9], the drag force depends mainly on the difference between the velocities of fluid \( U_{f,\zeta} \) and particle \( U_{p,i} \). For dense and reinforced conditions where particles are strictly confined, the drag force becomes more significant and depends mainly on the fluid velocity.

The force \( F_{h,i} \) accounting for the stress gradient of fluid imparted onto particle \( i \) having a volume \( V_{p,i} \) can be written by (Kafui et al., 2002):

\[ F_{h,i} = (-\nabla p + \nabla \cdot \tau_f) V_{p,i} \tag{7.13} \]

where \( p \) and \( \tau_f \) are the pressure and viscous stress tensors constituting the average stress tensor \( \xi_f \) of fluid that can be given by:

\[ \xi_f = -p \delta + \tau_f \tag{7.14} \]

where \( \delta \) is the identity (unit) tensor. The pressure gradient force generated due to the
difference in fluid pressure acting on particle $i$ can be separated into two parts: (1) the buoyancy force $F_{bo,i}$ and (2) the component $F_{vp,i}$ generated by the acceleration pressure gradient which represents the pressure difference of fluid flowing over a surface, resulting in an acceleration (Newton’s second law). These components can be computed individually, as shown below:

$$F_{vp,i} = -(\nabla p)V_{p,i}$$  \[7.15\]

$$F_{bo,i} = -\rho_f g V_{p,i}$$  \[7.16\]

In this study, the fluid-particle coupling technique was applied to model the hydraulic behaviour of coir fibres that were packed in various porous structures, which can result in a deviation of fluid velocity distributed over the fibre domain. The viscous force should therefore be considered as shown below:

$$F_{v \tau} = (\nabla \cdot \tau_f)V_{p,i}$$  \[7.17\]

Considering equations Eq. [7.9], [7.15], [7.16] and [7.17], the total fluid-particle interaction force can be represented as:

$$F_{f,i} = F_{d,i} + F_{vp,i} + F_{bo,i} + F_{v \tau}$$  \[7.18\]

7.3.3 Modelling fibres in DEM

The Parallel Bond Model (PBM) in DEM has proven to be reasonable when simulating a linear stress-strain behaviour and brittle fracture (Cho et al., 2007; Lisjak and Grasselli, 2014). Nguyen and Indraratna (2016) have also shown that the PBM can be applied well to capture the tension behaviour of jute and bamboo. However the tension test (represented in the following parts of this paper) carried out on the coir fibre in this study (see Fig. 7.4) revealed that the fibre had a non-linear stress-strain curve that requires the PBM to be modified accordingly.
Fig. 7.4 Tension test on individual coir fibre: (a) experiment; (b) DEM modelling; (c) stress-strain relationship by experiment and DEM modelling

A coefficient $\beta_b$, including shear and normal components, $\beta_{bn}$ and $\beta_{bs}$, which enable the bond model to capture various orders of displacements of particles in bonding are introduced to the conventional PBM proposed by Potyondy and Cundall (2004). The behaviour of particle bonding in DEM, including the tension, shear, and bending components
are then governed by the following equations:

\[
\Delta F_{bn,ij} = -k_{bn} (\Delta D_n)^{\beta_n} A_b \tag{7.19}
\]

\[
\Delta F_{bs,ij} = -k_{bs} (\Delta D_s)^{\beta_s} A_b \tag{7.20}
\]

\[
\Delta M_{bn,ij} = k_{bn} J_b \Delta \theta_n \tag{7.21}
\]

\[
\Delta M_{bs,ij} = k_{bs} I_b \Delta \theta_s \tag{7.22}
\]

In the above, the subscripts \(n\) and \(s\) indicate the normal and shear components, respectively; \(\Delta F, \Delta M\) are increments of the bond force \(F\) and moment \(M\), respectively, generated due to the relative translational and rotational displacements \(\Delta D_n, \Delta D_s, \Delta \theta_n, \Delta \theta_s\) between two particles in the bond; \(k_b\) is the bond stiffness. \(A_b, I_b\) and \(J_b\) are the area, moment of inertia, and the polar moment of inertia of the bond cross-section, respectively. These parameters are given by:

\[
A_b = \pi R_b^2 \tag{7.23}
\]

\[
I_b = \frac{1}{4} \pi R_b^4 \tag{7.24}
\]

\[
J_b = \frac{1}{2} \pi R_b^4 \tag{7.25}
\]

In the above, \(R_b\) is the radius of the bond region determined by:

\[
R_b = \lambda_b \min(R_i, R_j) \tag{7.26}
\]

where \(R_i\) and \(R_j\) are the radius of particles \(i\) and \(j\) in bonding; \(\lambda_b\) is the bond radius multiplier to optimise the virtual sharing area between two particles. The maximum normal and shear stresses acting on the bond periphery are computed as follows:
\[ \sigma_{\text{max}} = \frac{-F_{\text{bs}},j}{A_b} + \frac{|M_{\text{bs}},j|}{I_b} R_b \quad [7.27] \]

\[ \tau_{\text{max}} = \left| \frac{F_{\text{bn}},j}{A_b} + \frac{|M_{\text{bn}},j|}{J_b} R_b \right| \quad [7.28] \]

The bond is broken when either \( \sigma_{\text{max}} \) or \( \tau_{\text{max}} \) exceeds its corresponding strength \( \sigma_b \) and \( \tau_b \).

These parameters combined with \( k_{b,n} \), \( k_{b,s} \), \( \beta_{bn} \) and \( \beta_{bn} \) can be determined by primary tests such as testing the tension of real fibres. If the two components of the coefficient \( \beta_b \) in Eq. [7.19] and [7.20] are both equal to 1, then the conventional PBM is achieved. The radius of fibre particles in DEM was estimated based on the size of real fibres obtained from micro-analyses.

The time step of the fibre particle domain was selected with respect to the following equations:

\[ \Delta t_h = 2.87 \left( \frac{m_i^2}{R_e Y_e U_{p,\text{max}}} \right)^{0.2} \quad [7.29] \]

\[ \Delta t_r = \frac{\pi R}{(0.1631 \times \nu + 0.8766) \sqrt{\frac{\rho_p}{G}}} \quad [7.30] \]

where \( \nu \) is Poisson’s ratio; \( \rho_p \) is the density and \( G \) is the shear modulus of the particle; \( R \) denotes the average radius of particles and \( U_{p,\text{max}} \) is the maximum relative velocity of particles. \( R_e \), \( Y_e \) and \( m_e \) are the effective radii, Young’s modulus, and the mass of particles \( i \) and \( j \) in contact, respectively, and are computed as follows:

\[ A_b = \pi R_b^2 \quad [7.31] \]
\[ \frac{1}{Y_e} = \frac{1 - \nu_i^2}{Y_i} + \frac{1 - \nu_j^2}{Y_j} \]  

[7.32]

\[ J_b = \frac{1}{2} \pi R_b^4 \]  

[7.33]

For the coir fibres with a minimum diameter of 102 μm and an average density of 1160 kg/m³ used in this study, the time step of the DEM \( \Delta t_p = 1 \times 10^{-8} \) was found suitable for computation.

Contact between the fibre particles in DEM can be depicted on the basis of the spring-dashpot models, by adopting either linear or nonlinear spring and damping coefficients (Kloss et al., 2012). The reaction forces, including the normal and shear components of two particles in contact, are dependent on the overlap of particles (Cundall and Strack, 1979). Note that while the equivalent volume based diameter was considered for the porosity of fluid cells, the real diameter of the fibres was used to capture the contact between particles, as proposed by Nguyen and Indraratna (2016).

7.3.4 Calibrate the parameters of the fibre bond model

To obtain parameters for particle bonding, primary tension and bending tests were carried out on single fibres. Tension tests with a constant strain rate of 3 mm/min were carried out on 22 individual coir fibres which had their diameters measured in advance under optical microscope. Note that the number of fibres selected for testing was made with respect to previous studies (Defoirdt et al., 2010; Biswas et al., 2013) which have shown an acceptable accuracy of tension tests on single fibres. The tension force and displacement were recorded over time until the coir fibre broke. The averaged result from the tension test showing the non-linear stress-strain relationship of coir is shown in Fig. 7.4 where the curve indicates a brittle fracture of the coir fibres under tension. The average tensile strength of coir
fibre obtained in this study (i.e., $\sigma_{bn} = 188$ MPa with a standard deviation of 34 Mpa) corroborates with the values reported in a previous study by Defoirdt et al. (2010), which found the tensile strength of brown coir within a wide range, i.e., from 186 to 343 MPa. The components $k_{bn}$ and $\beta_{bn}$ in the numerical simulation were obtained on the basis of the experimental stress-strain curve. Fig. 7.4c shows how well the modified PBM with $k_{bn} = 1.01 \times 10^{11}$ Pa/m and $\beta_{bn} = 0.6$ in DEM can capture the tensile behaviour of the coir. Compared to the conventional PBM which can only capture the linear stress-strain relationship of material, the modified PBM can describe the tensile stress developed over the increment of axial strain more accurately. A slight deviation between the results obtained from the experiment and numerical method using the modified PBM, and the breakage of fibre at a strain of 9.5% indicates the success in applying the modified PBM to model coir fibre.

As well as the tension test, a bending test was carried out on coir fibres to determine the shear stiffness $k_{bs}$ of the fibre particle bond. A coir fibre was placed horizontally with one end fixed, while the other end of the fibre was subjected to a vertical load of 0.0545 g (Fig. 7.5a). The fibre was bent under the vertical load until it reached a stable condition with a certain deformation. This displacement of fibre was recorded accordingly. The properties of fibre, including its length, diameter, and density were determined; the fibre used in the bending test was approximately 0.3 mm in diameter and 43.2 mm long.

Fig. 7.5b shows the cross-section of the fibre while Fig. 7.5c shows its bending behaviour as simulated by the modified PBM incorporated in DEM under a vertical load of the same magnitude as applied in the laboratory. In this simulation, 145 particles with a diameter of 0.3 mm were generated and bonded. With regard to the normal stiffness $k_{bn}$ and the coefficient $\beta_{bn}$ determined from the tension test above, the shear stiffness $k_{bs}$ of $6.1 \times 10^{12}$ Pa/m and $\beta_{bs}$ of 1.0 matched the experimental results quite well. The bending behaviour of
fibre modelled by the DEM (Fig. 7.5c) was clearly the same as the tested coir fibre in the laboratory (Fig. 7.5a), where the tip of the fibre was stabilised at a vertical displacement of 17 mm.

Fig. 7.5 Bending test on individual coir fibre: (a) experimental model; (b) fibre cross-section under optical microscope observation; (c) DEM modelling

7.3.5 Structural characteristics of fibre drain

As described in the experiment determining the hydraulic conductivity of fibres, structural information of fibre drains, including the size and position of individual fibres, was
obtained after the hydraulic test. Note that in this study, the fluid-fibre media were mainly investigated with respect to laminar fluid flow that was assumed not to cause a significant disturbance to the fibre structure. The discharge velocity was not determined until the fluid flow became steady. Based on these parameters, fibre drains could be reconstructed numerically in 3D with the same porous features as those tested in the laboratory. The parameters used for bonding fibre particles that were gained from the calibration process (i.e., $k_{bn} = 1.01 \times 10^{11}$ Pa/m, $\beta_{bn} = 0.6$; and $k_{bs} = 6.1 \times 10^{12}$ Pa/m, $\beta_{bs} = 1$) were applied to these fibres.

Fig. 7.6 Capturing the position of fibre particles in a drain: (a) cross-section of dense coir fibres under microscope; (b) fibres modelled in DEM

In this study, various fibre fractions including dense, medium, and loose bundles were investigated. Fig. 7.6a shows a typical cross-section of a dense fibre bundle with a porosity of 0.35, where 160 fibres are distributed randomly within a 4 mm diameter tube. The diameters of the fibre in this case ranges from 112 to 420 $\mu$m, with an average diameter of 235 $\mu$m, but note that due to the large number of fibres packed inside the tube, their locations are relatively uniform. With respect to the coarse-grid approximation method which requires the minimum size of fluid cells be greater than the diameter of particles in this study (O'Sullivan,
2011), the porosity of dense fibres were more homogeneous over the fluid cells than the looser ones where fibres have more space to position themselves. Fig. 7.6b shows how DEM could capture the position of fibres within the tube accurately, to ensure a similar porous structure between the DEM and reality. The position of individual fibres in the whole fibre package could be determined exactly on the basis of micro-analyses and this information was then incorporated into the numerical framework.

![Fig. 7.6b](image)

(a) Dense non-twisted fibres, $n_f = 0.351$
(b) Medium non-twisted fibres, $n_f = 0.682$
(c) Loose non-twisted fibres, $n_f = 0.850$
(d) Dense twisted fibres, $n_f = 0.330$
(e) Medium twisted fibres, $n_f = 0.628$
(f) Loose twisted fibres, $n_f = 0.822$

Fig. 7.7 Segments of fibre bundles built in DEM with different porous structure: twisted and non-twisted fibres

The segments of fibre drains for twisted and non-twisted bundles with different magnitudes of fibre fraction built in DEM are shown in Fig. 7.7. All these fibre bundles have
the same scale (i.e., cylindrical domain with a diameter of 4 mm), and the fibre varies in
diameter from 110 to 460 µm. Fig. 7.7 a, b, and c represent the loose, medium, and dense
bundles where fibres are arranged randomly without twisting, while in Fig. 7.7 d, e and f,
fibres with different porosity are twisted with an approximate angle of 20°. In a non-twisted
format, individual fibres are kept almost straight that creates a porous structure consisting of
parallel channels, whereas twisted fibres have more complex porous characteristics with
longer and more tortuous fluid paths.

Fibres in geoengineering applications might vary from non-twisted to highly twisted,
depending on their individual roles. Twisted bundles where the fibres are tightened closely
together are usually denser and more robust, but less permeable than non-twisted ones. For
example, coir fibres that are used for the cores of natural fibre drains are usually twisted
highly, whereas jute fibres mainly used for filtering and surface draining are usually not
twisted as much. Therefore the hydraulic behaviour of a fibre drain should be considered in
close conjunction with the type of fibrous structure and their practical applications.

7.3.6 Modelling fluid flow through fibrous media

A fluid draining through fibrous media established in DEM was generated in CFD
such that the fluid domain was a cylinder, i.e., same as the internal diameter of the tube used
for the laboratory tests. Fluid flowed from one end of the domain to the other under the
pressure difference between the inlet and the outlet. This pressure difference was created with
respect to the hydraulic heads applied in the laboratory. Note that only laminar flow with a
hydraulic gradient of less than or equal to 1 was considered in this numerical approach. The
fluid velocity at the outlet was obtained from the numerical computation. With respect to the
drop in pressure $\Delta p$ and fluid velocity $U_{f,s}$ at the outlet, the hydraulic conductivity of a fibre
drain with a length $L$ can be estimated by:
The fluid domain was discretised into a number of individual cells with a minimum size that was larger than the biggest diameter of fibre particles deposited in the tube. The porosity in each cell was computed individually and was then used to solve the Navier-Stokes equations. To account for the influence of various porous structures in different fibre drains on fluid behaviour, the fluid domain was discretised exactly the same for all cases investigated. Fig. 7.8a demonstrates how the cylindrical fluid domain is meshed with respect to the largest diameter of fibre particles of 460 μm.

Fig. 7.8 Meshing fluid domain: (a) longitudinal discretization; (b) cross-section of fluid domain with the fluid velocity distribution in relation to fibre particles
In the CFD framework, the critical time step $\Delta t_f$ was given by:

$$\Delta t_{f,m} = \frac{\Delta x}{|U_f|}$$  \[7.35\]

where $\Delta x$ is the size of the fluid cell in the direction of fluid flow.

In this study, $\Delta t_f=1 \times 10^{-6}$ was used with the exchange between the CFD and DEM carried out in every 100 time steps $\Delta t_p$.

To account for the friction in the tube that could affect how the fluid would behave, a no-slip boundary condition was applied onto the walls of fluid domain. Apart from the path that the fluid would take through the fibre domain, fluid paths were extended at the inlet and outlet to ensure there would be no effect of boundary condition and fluid flow would be fully developed.

Fig. 7.8 represents a typical fibre drain built in DEM subjected to a fluid flowing along its longitudinal axis. Fluid pressure decreases from the inlet to the outlet over the fibre domain under a hydraulic gradient of 1. The distribution of fluid velocity and fibre size in a cross-section, extracted from the fibre-fluid system, is shown in Fig. 7.8b which indicates that the fluid velocity is zero at the boundary (no-slip boundary) and varies according to how the fibre is distributed.

7.4 Results and Discussion

7.4.1 Experimental results

It is well known that the hydraulic behaviour of a porous material should be considered with respect to the hydraulic gradient of fluid flow. Fig. 7.9 shows how the discharge velocity of fluid flowing through a coir fibre drain varies with the measured hydraulic gradients. According to Darcy’s law and for a small range of hydraulic gradients,
fluid has laminar flow and there is a linear relationship between the superficial velocity and hydraulic gradient \( U_{fs} = k \times i \). An increasing hydraulic gradient generates a more dynamic portion to the flow (turbulent flow zone) making the relationship between the discharge velocity and hydraulic gradient non-linear. With the coir fibrous media used in this study, the experimental results (Fig. 7.9) indicate the laminar flow zone generated when the hydraulic gradient is less than 1. When the hydraulic gradient is more than 1, fluid flow turns into a transition zone with an increasing portion of turbulent flow. Other studies (Akagi, 1994; Bergado et al., 1996; Rawes, 1997) have recommended that the largest hydraulic gradient needed to maintain laminar flow in discharge capacity tests of conventional drains should be between 0.1 and 1. However, it is important to remember that these suggested values might vary depending on the features of the testing models such as scale, confining pressure, and drain characteristics.

![Diagram](image)

**Fig. 7.9** Experimental discharge velocity of fluid flowing through fibre drain over hydraulic gradient

There is an obvious relationship between the porosity and hydraulic conductivity of porous media, as confirmed in a number of previous studies (Carman, 1937; Sullivan, 1942).
Fig. 7.10a shows how the hydraulic conductivity ($k$) of coir fibres depends on the porosity ($n_f$) observed in this study, such that as $n_f$ decreases from 0.85 to 0.33, hydraulic conductivity apparently decreases and this reduction steepens when $n_f < 0.5$.

![Graph showing hydraulic conductivity vs. porosity](image)

Fig. 7.10 Hydraulic conductivity of coir fibres obtained by: (a) experimental; and (b) in comparison with the K-C analytical methods

Fig. 7.10a also indicates a clear difference between the hydraulic behaviour of twisted
and non-twisted fibre bundles; where \( n_f > 0.65 \), these two fibre structures show a slight difference in hydraulic conductivity, but as the fibre becomes denser, there is a clear deviation between the two curves. Twisted bundles have a more complex porous structure than non-twisted ones where individual fibres are almost straight (parallel channels of porosity), the permeability is hence lower. With very dense fibres i.e., \( n_f = 0.35 \), the hydraulic conductivity of a twisted fibre drain decreases to approximately \( 1 \times 10^{-5} \text{ m/s} \), but it is around \( 6.5 \times 10^{-5} \text{ m/s} \) for non-twisted types. The denser the fibres being created, the bigger the gap between the two curves of hydraulic conductivity. This experimental result indicates that the hydraulic behaviour depends on the porous characteristics of fibre drains, and suggests that this relationship should be considered when designing the discharge capacity of fibre drains installed for soft soil improvement.

7.4.2 Analytical results

<table>
<thead>
<tr>
<th>Test</th>
<th>Twisted fibres</th>
<th>Non-Twisted fibres</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Porosity</td>
<td>Average diameter</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( d_f ) (m)</td>
</tr>
<tr>
<td>1</td>
<td>0.330</td>
<td>( 2.362 \times 10^{-4} )</td>
</tr>
<tr>
<td>2</td>
<td>0.418</td>
<td>( 2.346 \times 10^{-4} )</td>
</tr>
<tr>
<td>3</td>
<td>0.523</td>
<td>( 2.396 \times 10^{-4} )</td>
</tr>
<tr>
<td>4</td>
<td>0.628</td>
<td>( 2.407 \times 10^{-4} )</td>
</tr>
<tr>
<td>5</td>
<td>0.822</td>
<td>( 2.318 \times 10^{-4} )</td>
</tr>
</tbody>
</table>

Table 7.2 Parameters for the permeability estimated by the Kozeny-Carman solution

With reference to the KC equation, hydraulic conductivity calculated over the porosity is shown in Fig. 7.10b, and compared with the experimental results. In this investigation the properties of fibre drains, including the average fibre diameters and porosities obtained experimentally were adopted (Table 7.2). The fibres were assumed to be cylindrical with an
equivalent diameter computed based on the constant cross-sectional area. As Fig. 7.10b shows, for fibre drains with $n_f > 0.6$ (medium to loose fibres), the KC analytical method captures the hydraulic conductivity of the media for twisted and non-twisted forms quite well. For this range of porosity, the biggest deviation between the analytical and experimental results is about 25% and this is usually acceptable when using the KC approach to predict the permeability of fibrous materials (Gutowski et al., 1987). Note that this accuracy only remained within a narrow range of porosity i.e., $n_f > 0.6$. Since the fibre fraction is increasing, the analytical curves deviate significantly from the experimental ones, while for the dense fibre systems with $n_f < 0.5$, the analytical method results in a far greater difference in hydraulic conductivity compared to the laboratory data. The hydraulic trend predicted by the analytical method for dense fibres deviates completely from the trend observed experimentally, especially for the twisted fibres.

In this analysis, the Kozeny constants $k_k$ of 10 and 13.5 were used for non-twisted and twisted fibres, respectively, and these were acceptable at estimating the permeability of medium and loose fibres. However, compared to previous studies (Sullivan, 1942; Sherony and Kintner, 1971) who generally suggested $k_k$ less than 10 for fibrous beds, these values are larger because of the differences in the porous characteristics of fibres used in different studies. While previous studies used fibres with a parallel arrangement in hydraulic tests, this study created fibre bundles with more complex but realistic structures (non-twisted versus twisted fibres). Moreover, the Kozeny constant was influenced by the specific surface area and the range of porosity, which actually depends directly on the shape and size of the fibres (Li and Gu, 2005; Ozgumus et al., 2014). Previous studies used much smaller fibres, e.g., with an equivalent diameter of 7.6 μm (Sullivan, 1942) and 10 μm (Sherony and Kintner, 1971), whereas in this study the average diameter of coir fibre was 236 μm. Li and Gu (2005) also found a relatively high value of $k_k$ i.e., 12.75 when they used fibres having a
diameter of 170 µm in their experimental study. Although the wall-fluid friction was small due to a smooth internal surface of the tube wall adopted, it has not been considered in this investigation.

7.4.3 Numerical results

![Diagram showing variation of parameters over fluid cells: (a) porosity; and (b) fluid velocity.](image)

Fig. 7.11 Variation of parameters over fluid cells: (a) porosity; and (b) fluid velocity.

Fig. 7.11 represents variations in fluid velocity at specific locations ($r_o = 0.8, 1.2$ and 1.6 mm) along the axis of 100 mm long drain simulated by the coupled CFD-DEM method. The porosity varies along the drain length (Fig. 7.11a), resulting in a corresponding variation of fluid velocity (Fig. 7.11b). However, the fluid velocity is smaller near the boundary (e.g., $r_o = 1.6$ mm) at which the no-slip condition is imposed, although the porosity at this location
is higher. These observations are in agreement with a past study by Chen and Papathanasiou (2007), where it was concluded that non-uniform void distribution in inhomogeneous fibrous structure is expected to give varied flow velocity in the medium.

Hydraulic conductivity from the numerical approach matches those obtained from the experiments, as shown in Fig. 7.12. Particularly, the hydraulic conductivity of loose and medium fibres with \( n_f > 0.55 \) is captured well by the numerical method. An insignificant deviation in hydraulic conductivity obtained from the numerical and experimental methods claims an acceptable accuracy of prediction for loose and medium fibres, however, the gap between these curves does expand when the fibres are denser. In fact when the porosity falls below 0.4, the differences between the numerical and experimental approaches are more apparent, particularly in twisted fibres.

![Fig. 7.12 Hydraulic conductivity predicted by the CFD-DEM approach in comparison with the experimental and analytical methods](image)

The CFD-DEM coupling technique used in this study was successful at capturing how porous structure could influence on hydraulic behaviour. Fig. 7.12 shows a deviation in the hydraulic conductivity of the non-twisted and twisted drains modelled by the numerical method that matches the experimental results. For the same discretisation of the fluid domain,
Fig. 7.13 Fluid flowing through different fibrous porous structures: (a) non-twisted; and (b) twisted fibres; captured by the CFD-DEM method.

different fibre structures with unequal porous distribution result in a variation of parameters such as the porosity ($n_f$) and fluid velocity ($U_f$). Fig. 7.13 shows how the numerical approach can capture the deviation in fluid flowing through different porous structures of fibrous media (non-twisted and twisted fibres). In Fig. 7.13, arrows represent fluid paths with their different colours showing the variation of fluid velocity through micro-porous media. Compared to Fig. 7.13a where fluid flow occurs parallel to the fibre direction, the fluid flow occurs along more tortuous channels in the twisted fibres in Fig. 7.13b. However the gap between the non-
twisted and twisted curves predicted by the numerical approach in the regime of very low porosity was smaller than the one measured experimentally as shown in Fig. 7.12, which indicates some limitations of the coupling technique in its ability to capture the accurate hydraulic behaviour in very dense media.

The discrepancies discussed above between the computational and laboratorial investigations can be explained by several major issues, including: (i) the no-slip boundary used in the fluid dynamics might not describe the frictional interaction between the fluid and tube walls accurately; (ii) using coarse meshing for the fluid domain could limit of its ability to capture fluid distribution due to complex porous structures, resulting in inaccurate hydraulic behaviour predicted by the numerical method in dense fibres.

7.5 Conclusions

An investigation using experimental, analytical and numerical approaches on the hydraulic behaviour of longitudinal flow through brown coconut coir fibres was described in this paper. Two basic types of fibre structure, non-twisted and twisted bundles, were considered. Fibrous structures were reconstructed on the numerical framework based on a series of micro-analyses which enabled the porous characteristics to be understood better. The results from the numerical solution were validated with the experimental and Kozeny-Carman (KC) analytical methods, and the following conclusions can be drawn:

7.5.1 The hydraulic behaviour of fibrous porous materials depends not only on the porosity but also on the void characteristics of the fibrous media. For example, parallel assembly of fibres (non-twisted), for the same porosity, resulted in a greater permeability than the twisted type in which the fibres create a more complex and longer fluid path.

7.5.2 The KC analytical approach could predict the permeability of the fibrous system for $n_f > 0.6$, but there were obvious discrepancies when determining the permeability of
denser fibres from those measured in the laboratory. With loose and medium fibrous media \((n_f > 0.6)\), the Kozeny constants \(k_k\) of 10 and 13.5 used in the KC solution could be regarded as sufficiently reliable to compute the hydraulic conductivity of non-twisted and twisted fibres, respectively.

7.5.3 By introducing the coefficient \(\beta_b\) to the conventional PBM, the modified PBM used for bonding particles becomes more flexible to capture different forms of fibre stress-strain relationships, so that more types of fibres can be simulated by the numerical approach.

7.5.4 The CFD-DEM coupling technique could depict how porous characteristics affected the hydraulic behaviour of fibrous media, particular those with \(n_f > 0.4\). It could also capture the various fluid parameters (e.g., fluid velocity) stemming from differences in the micro-porous structure within the fibre bundle (drain), and was therefore more accurate in predicting the hydraulic conductivity than the conventional KC method which relies heavily on the empirical constant \(k_k\).

7.6 Acknowledgements

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Chapter 8 CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

After a comprehensive literature review of natural prefabricated vertical drains (NPVDs) shown in Chapter 2, a series of studies were carried out to clarify the limitations of previous studies such as the paucity by considering biodegradation characteristics of drains and their influence on soft soil consolidation, as well as the hydraulic properties of NPVDs in light of novel solutions proposed to enhance their design efficiency. A significant effort was made to establish analytical and numerical frameworks which would help to optimise the prediction of soil consolidation by considering the biodegradation of drains, and the hydraulic properties of NPVDs.

The analytical and numerical evaluations presented in Chapter 3 showed that consolidation could be retarded significantly due to the severe biodegradation of NPVDS exposed to adverse media; when the discharge capacity decreased to a relatively small level, the dissipation of excess pore pressure became insignificant. This study, therefore, suggests there is a need to consider the biodegradation of NPVDs when designing soil consolidation induced by natural fibre drains. The proposed analytical and numerical methods in which the biodegradation of drains was incorporated into the governing equations of soil consolidation achieved a certain success at capturing the influence of biodegradation on consolidation, so they can be useful for practical designs in large embankment projects.

Chapter 4 presented a laboratory investigation into the biodegradation of NPVDs made from jute and coir fibres with an in-depth analysis on their microbial and biochemical properties. The results showed that jute fibres responded differently to soil with varying acidity such that the more acidic the medium, the less biodegradable the fibres would be. Although soils could have contain bacteria such as sulphate reducing bacteria which can
consume organic matter, those microbes could not directly decompose cellulose based materials such as jute fibres without the availability of cellulose degrading bacteria, particularly the families Ruminococaceae and Bacillaceae (the genus Bacillus) and Clostridia (the genus Clostridium). This is because cellulose is a macro-molecule which must be broken into monomers, i.e., glucoses which serve as biotic foods or fuel for microbes such as sulphate reducing bacteria. The study also indicated that jute with about 80% cellulose and only 10% lignin could experience a much more rapid degradation compared to coir which was made of approximately 40% lignin. Therefore a pre-investigation into biological characteristics of soil is essential to ensure that natural fibre drains are applied properly in any infrastructure project considering NPVDs.

The influence of micro-characteristics on the hydraulic conductivity of fibre drains such as the diameter, shape, the uniformity in size and twisting angle of fibres was shown in Chapter 5. The outcomes showed that larger diameter fibres had a higher permeability, for example, coir fibres had an average diameter of 235 \( \mu \text{m} \), making its permeability much greater than jute fibres having an average diameter of 41.8 \( \mu \text{m} \). Coir fibres were also more rounded than jute, which resulted in a higher discharge capacity. The study indicated that fibres with a larger dispersion in size had smaller hydraulic conductivity, and also the more the fibre was twisted, the lower the discharge capacity became. These properties suggest that attention should be paid to the micro-characteristics of fibres when designing and manufacturing NPVDs.

Chapter 6 presented a fundamental concept to model natural fibre drains using CFD-DEM coupling, in which DEM was used to simulate fibres and CFD was used to describe fluid behaviour. The results of using DEM to model tensile and bending behaviour were then compared to previous studies, including analytical and numerical methods, and they indicated that the numerical simulation was justifiable. Flow properties such as the velocity and
pressure varying over fibre domain could be captured well by the proposed method, with a good agreement shown between the longitudinal permeability from this study in comparison to previous studies employing alternative approaches. These results also indicated that CFD-DEM coupling is a promising method of modelling various fluid-particle systems, i.e., the interaction of soil-fibre drains during fluid flow.

In Chapter 7, a detailed application of CFD-DEM coupling to model coir fibre drains was shown. A modified Parallel Bond Model (PBM) with a detailed process to verify its parameters was proposed to amend the limitation of conventional PBM which could not capture the nonlinear stress-strain relationship of natural fibres such as coconut coir. The hydraulic conductivity resulting from this numerical implementation agreed well with the experimental data for medium and loose fibres, despite a certain deviation in dense media. The micro-hydraulic behaviour of fluid flowing through different porous structures, i.e., twisted and non-twisted fibres, could also be captured well by this numerical approach; this indicated that the coupling method had advantages over past solutions when modelling micro-interactions between fluid and particles in geoengineering applications such as NPVDs.

8.2 RECOMMENDATIONS

Although the proposed analytical and numerical methods can predict how the biodegradation of NPVDs can affect the radial consolidation of soil, the reduced form of drain discharge capacity which plays a key role in the accuracy of these predictions has not been clarified adequately by the experimental and field observations. Therefore a detailed investigation into a reduction in the discharge capacity of NPVDs is essential to further improve the model. In situ measurements on the biodegradation of drains in light of soil consolidation, particularly in adverse media, are also needed to validate the model.

The biodegradation of NPVDs was investigated with respect to different acidic soils
created using commercial vinegar. However, this method might certainly lead to a considerable disturbance of the natural microbial characteristics of the soil, and cause a deviation of the results compared to those occurring in the field. Therefore, natural soils with different acidities and undisturbed biological properties should be used for the investigation. This approach can ensure an identical field environment, thus a more insightful understanding of the biodegradation characteristics of natural fibre drains.

The major limitation of the numerical studies presented in Chapters 6 and 7 was that the interaction between fluid and fibres was investigated without soil particles in tandem; this resulted in a significant deviation in the field. Undoubtedly, more computational effort is required when a large number of soil particles are introduced to DEM to interact with fluid flow. This improvement would enable the study of clogging which fundamentally relies on soil-fibre interaction at both micro- and macro-levels. A corresponding experimental study to investigate the clogging behaviour of natural fibre drains is needed to validate the numerical results.

This thesis also presented a number of approaches to bond fibre particles in DEM, none of which are currently able to capture the biodegradation of natural fibres. A new bond model which could capture various tensile and bending properties and also model the time-dependent engineering characteristics of natural fibres would be most beneficial for naturally occurring geomaterials. In order to create such a model, intensive programming needs to be executed and incorporated it into an open source DEM framework. In this computational program, the proper understanding of biodegradation characteristics of natural fibre plays a key role, thus a detailed experimental study addressing this unique feature of natural fibres is highly recommended in the future.
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Fig. A1 Bacterial community in soil/container 1 (at 40 cm depth)
Fig. A2 Bacterial community at the surface layer of soil/container 1 (at 5 cm depth)
Fig. A3 Bacterial community in soil/container 2 (at 40 cm depth)
Fig. A4 Bacterial community in soil/container 3 (at 40 cm depth)