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EXPERIMENTAL AND NUMERICAL INVESTIGATIONS INTO HYDRAULIC BEHAVIOUR OF COIR FIBRE DRAIN

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Abstract

Over many decades, natural fibre bundles have been used widely for drainage and filtration applications because of their favourable hydraulic conductivity and abundance in Asian countries. In recent times, natural (biodegradable) coir and jute drains that are environmentally-friendly have been considered in lieu of conventional geosynthetic wick drains for soft clay consolidation in Australian coastal regions. However there is a lack of computational framework to predict the hydraulic behaviour of fibre drains on the basis of micromechanical (fabric) characteristics. Employing the Computational Fluid Dynamics (CFD) coupled with the Discrete Element Method (DEM) to model the hydraulic behaviour of fibrous materials has shown promise in an earlier study (Nguyen and Indraratna 2016), which considered an idealised parallel arrangement of fibres for simplicity. This paper aims to broaden the application of the coupled CFD-DEM technique to real fibres (coconut coir) considering both non-twisted and twisted fibre bundles that have more complex porous structure. The hydraulic conductivity determined from the numerical approach is validated with the experimental results, and also compared to the analytical prediction based on the conventional Kozeny-Carmen (KC) approach. The current study shows that the CFD-DEM technique can capture well the fluid flow characteristics of a non-uniform fibrous structure, including dense twisted coir bundles.

Keywords: geomaterials; natural fibre drains; hydraulic conductivity; fluid-particle coupling; Kozeny-Carmen approach.

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 2009). 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 (Kim 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-Carmen (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:

$$(1) \quad K = \frac{D_f^2 n^3}{16k_k(1-n)^2}$$

where D_f is the average diameter of fibres in the drain, n 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.

Experimental investigation on the longitudinal permeability of coir fibres

Fibrous drain

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 (NJBFI) 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 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.

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. 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. 1b and 1c show how non-twisted and twisted bundles can be generated using coir fibres, respectively.

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. 2a).

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. 2b and 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 2008). The dynamic viscosity of the water used in this study was 1.004×10^{-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. 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. 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 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_f recorded at the outlet of the fibre tube over time t , the hydraulic conductivity k was estimated as follows:

$$(2) \quad k = \frac{V_f R_t}{i A_t t}$$

where R_t is the correction factor for the viscosity of water, depending on the water temperature (ASTM 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_f was measured at a steady state of flow.

140 Numerical modelling of hydraulic behaviour of fibrous material

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

147 Fluid behaviour

148 This study assumed an incompressible fluid with conservation of mass where the fluid
149 variables, including the velocity U_f and pressure p are governed in individual cells as
150 represented by the following Navier-Stokes equations.

$$(3) \quad \frac{\partial n}{\partial t} + \nabla \cdot (nU_f) = 0$$

$$(4) \quad \frac{\partial(\rho_f n U_f)}{\partial t} + \nabla \cdot (\rho_f n U_f U_f) = -n \nabla p - f_p + \nabla \cdot (n \tau) + n \rho_f g$$

151 In the above equations τ denotes the viscous stress tensor while ρ_f is the fluid density
152 while. The porosity n of a certain fluid cell is defined as the ratio of the void volume in a cell
153 to its total volume: $n = V_v/V_c = 1 - V_p/V_c$ where V_v , V_p are the volumes of the void and particles
154 occupied in a cell, respectively; and V_c is the volume of the cell. f_p is the mean volumetric
155 particle-fluid interaction force representing the effect of the solid phase on the fluid phase
156 within the cell. By considering that the fluid cell α contains n_p particles, f_p of cell α can be
157 estimated by Equation (5) as follows:

$$(5) \quad f_{p,\alpha} = \sum_{i=1}^{n_{p,\alpha}} \varpi_{i\alpha} \left(\frac{F_{p,i}}{V_{c,\alpha}} \right)$$

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

The viscous stress tensor τ can be written in relation to the fluid viscosity μ_f and velocity U_f as follows:

$$(6) \quad \tau = \mu_f \left[(\nabla U_f) + (\nabla U_f)^T \right]$$

Particle behaviour

The motion of particle i in DEM, including the rotational and translational components, is governed by the following equations:

$$(7) \quad m_i \frac{dU_{p,i}}{dt} = \sum_{j=1}^{n_i^c} F_{c,ij} + F_{f,i} + F_{g,i}$$

$$(8) \quad I_i \frac{d\omega_{p,i}}{dt} = \sum_{j=1}^{n_i^c} M_{c,ij}$$

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_i^c 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 α , according to De Felice's solution which was used and verified by Zhou et al. (2010), is given by:

$$(9) \quad F_{d,i} = \frac{1}{8} C_{d,\alpha} \rho_f \pi D_{p,i}^2 n_\alpha^2 (U_{f,\alpha} - U_{p,i}) |U_{f,\alpha} - U_{p,i}| n_\alpha^{-\chi}$$

where $U_{f,\alpha}$ and $U_{p,i}$ are referred to as the averaged velocity of fluid in cell α and the velocity of particle i residing in cell α , 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:

$$(10) \quad C_{d,i} = \left(0.63 + \frac{4.8}{\sqrt{Re_{p,i}}} \right)^2$$

where $Re_{p,i}$ is the particle Reynolds number which is determined by:

$$(11) \quad Re_{p,i} = \frac{n_\alpha \rho_f D_{p,i} |U_{f,\alpha} - U_{p,i}|}{\mu_f}$$

In Equation (9) the porosity function $n_\alpha^{-\chi}$ represents the presence of other particles in cell α in relation to the power factor χ which is a function of the Reynolds number $Re_{p,i}$ and is estimated by:

$$(12) \quad \chi = 3.7 - 0.65 \exp \left[-\frac{(1.5 - \log_{10} Re_{p,i})^2}{2} \right]$$

Note that according to Equation 9, the drag force depends mainly on the difference between the velocities of fluid $U_{f,\alpha}$ 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):

$$(13) \quad F_{h,i} = (-\nabla p + \nabla \cdot \tau) V_{p,i}$$

where p and τ are the pressure and viscous stress tensors constituting the average stress tensor ξ_f of fluid that can be given by:

$$(14) \quad \xi_f = -p\delta + \tau$$

where δ 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: (i) the buoyancy force $F_{b,i}$, and (ii) the component $F_{\nabla p,i}$ 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:

$$(15) \quad F_{\nabla p,i} = -(\nabla p) V_{p,i}$$

$$(16) \quad F_{b,i} = -\rho_f g V_{p,i}$$

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:

$$(17) \quad F_{\nabla, \tau, i} = (\nabla \cdot \tau) V_{p, i}$$

Considering equations (9), (15), (16) and (17), the total fluid-particle interaction force can be represented as:

$$(18) \quad F_{f, i} = F_{d, i} + F_{\nabla p, i} + F_{b, i} + F_{\nabla \cdot \tau, i}$$

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. 4) revealed that the fibre had a non-linear stress-strain curve that requires the PBM to be modified accordingly.

A coefficient β_b including shear and normal components, β_{bn} and β_{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:

$$(19) \quad \Delta F_{bn, ij} = -k_{bn} (\Delta D_n)^{\beta_{bn}} A_b$$

$$(20) \quad \Delta F_{bs, ij} = -k_{bs} (\Delta D_s)^{\beta_{bs}} A_b$$

$$(21) \quad \Delta M_{bn, ij} = k_{bs} J_b \Delta \theta_n$$

$$(22) \quad \Delta M_{bs,ij} = k_{bn} I_b \Delta \theta_s$$

220 In the above, the subscripts n and s indicate the normal and shear components, respectively;
 221 $\Delta F, \Delta M$ are increments of the bond force F and moment M , respectively, generated due to
 222 the relative translational and rotational displacements $\Delta D_n, \Delta D_s, \Delta \theta_n, \Delta \theta_s$ between two
 223 particles in the bond; k_b is the bond stiffness. A_b, I_b and J_b are the area, moment of inertia, and
 224 the polar moment of inertia of the bond cross-section, respectively. These parameters are
 225 given by:

$$(23) \quad A_b = \pi R_b^2$$

$$(24) \quad I_b = \frac{1}{4} \pi R_b^4$$

$$(25) \quad J_b = \frac{1}{2} \pi R_b^4$$

226 In the above, R_b is the radius of the bond region determined by:

$$(26) \quad R_b = \lambda \min(R_i, R_j)$$

227 where R_i and R_j are the radius of particles i and j in bonding; λ is the bond radius multiplier to
 228 optimise the virtual sharing area between two particles. The maximum normal and shear
 229 stresses acting on the bond periphery are computed as follows:

$$(27) \quad \sigma_{\max} = \frac{-F_{bn,ij}}{A} + \frac{|M_{bs,ij}|}{I} R_b$$

$$(28) \quad \tau_{\max} = \frac{|F_{bs,ij}|}{A} + \frac{|M_{bn,ij}|}{J} R_b$$

230 The bond is broken when either $\sigma_{\max}$ or $\tau_{\max}$ exceeds its corresponding strength σ_b and τ_b .

231 These parameters combined with $k_{b,n}, k_{b,s}, \beta_{bn}$ and β_{bs} can be determined by primary tests
 232 such as testing the tension of real fibres. If the two components of the coefficient β_b in

equations (19) and (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:

$$(29) \quad \Delta t_h = 2.87 \left(\frac{m_e^2}{R_e Y_e^2 U_{p,\max}} \right)^{0.2}$$

$$(30) \quad \Delta t_r = \frac{\pi R}{(0.1631 \times \nu + 0.8766)} \sqrt{\frac{\rho_p}{G}}$$

where ν is Poisson's ratio; ρ_p is the density and G is the shear modulus of the particle; R denotes the average radius of particles and $U_{p,\max}$ 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:

$$(31) \quad \frac{1}{R_e} = \frac{1}{R_i} + \frac{1}{R_j}$$

$$(32) \quad \frac{1}{Y_e} = \frac{1-\nu_i^2}{Y_i} + \frac{1-\nu_j^2}{Y_j}$$

$$(33) \quad \frac{1}{m_e} = \frac{1}{m_i} + \frac{1}{m_j}$$

For the coir fibres with a minimum diameter of 102 μm and an average density of 1160 kg/m^3 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).

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. 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 β_{bn} in the numerical simulation were obtained on the basis of the experimental stress-strain curve. Fig. 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. 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. 5b shows the cross-section of the fibre while Fig. 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 β_{bn} determined from the tension test above, the shear stiffness k_{bs} of 6.1×10^{12} Pa/m and β_{bs} of 1.0 matched the experimental results quite well. The bending behaviour of fibre modelled by the DEM (Fig. 5c) was clearly the same as the tested coir fibre in the laboratory (Fig. 5a), where the tip of the fibre was stabilised at a vertical displacement of 17 mm.

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.

In this study, various fibre fractions including dense, medium, and loose bundles were investigated. Fig. 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 μm , with an average diameter of 235 μm , 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. 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.

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. 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 a, b, and c represent the loose, medium, and dense bundles where fibres are arranged randomly without twisting, while in Fig. 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 geoenvironmental 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.

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 Δp and fluid velocity $U_{f,s}$ at the outlet, the hydraulic conductivity of a fibre drain with a length L can be estimated by:

$$(34) \quad k = \frac{\rho_f g U_{f,s} L}{\Delta p}$$

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. 8a demonstrates how the cylindrical fluid domain is meshed with respect to the largest diameter of fibre particles of 460 μm .

In the CFD framework, the critical time step Δt_f was given by:

$$(35) \quad \Delta t_{f,m} = \frac{\Delta x}{|U_f|}$$

where Δx 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 Δt_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. 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. 8b which indicates that the fluid velocity is zero at the boundary (no-slip boundary) and varies according to how the fibre is distributed.

Results and Discussion

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. 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 ($U_{f,s} = k \times i$). 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. 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.

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. 10a shows how the hydraulic conductivity (k) of coir fibres depends on the porosity (n) observed in this study, such that as n decreases from 0.85 to 0.33, hydraulic conductivity apparently decreases and this reduction steepens when $n < 0.5$.

Fig. 10a also indicates a clear difference between the hydraulic behaviour of twisted and non-twisted fibre bundles; where $n > 0.65$, 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., $n = 0.35$, the hydraulic conductivity of a twisted fibre drain decreases to approximately 1×10^{-5} m/s, but it is around 6.5×10^{-5} 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.

Analytical results

With reference to the KC equation, hydraulic conductivity calculated over the porosity is shown in Fig. 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 2). The fibres were assumed to be cylindrical with an equivalent diameter computed based on the constant cross-sectional area.

As Fig. 10b shows, for fibre drains with $n > 0.6$ (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., $n > 0.6$. Since the fibre fraction is increasing, the analytical curves deviate significantly from the experimental ones, while for the dense fibre systems with $n < 0.5$, 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.

Numerical results

Fig. 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. 11a), resulting in a corresponding variation of fluid velocity (Fig. 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 [ENREF 8](#)), 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. 12. Particularly, the hydraulic conductivity of loose and medium fibres with $n > 0.55$ 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.

The CFD-DEM coupling technique used in this study was successful at capturing how porous structure could influence on hydraulic behaviour. Fig. 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, different fibre structures with unequal porous distribution result in a variation of parameters such as the porosity (n) and fluid velocity (U_f). Fig. 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. 13, arrows represent fluid paths with their different colours showing the variation of fluid velocity through micro-porous media. Compared to Fig. 13a where fluid flow occurs parallel to the fibre direction, the fluid flow occurs along more tortuous channels in the twisted fibres in Fig. 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. 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.

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-Carmen (KC) analytical methods, and the following conclusions can be drawn:

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.
2. The KC analytical approach could predict the permeability of the fibrous system for $n > 0.6$, but there were obvious discrepancies when determining the permeability of denser fibres from those measured in the laboratory. With loose and medium fibrous media ($n > 0.6$), 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.
3. By introducing the coefficient β_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.
4. The CFD-DEM coupling technique could depict how porous characteristics affected the hydraulic behaviour of fibrous media, particular those with $n > 0.4$. 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

489 predicting the hydraulic conductivity than the conventional KC method which relies
490 heavily on the empirical constant k_k .

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TABLES

Density (kg/m ³)	Water content (%)		Tensile strength (MPa)	Elastic Modulus (GPa)	Diameter (mm)	Length (mm)
	Dry	Saturated				
1160	14	94	188±34	4.2	0.102- 0.495	65-250

Table 1 Physical properties of brown coir fibres

Test	Twisted fibres		Non-Twisted fibres	
	Porosity	Average diameter D_f (m)	Porosity	Average diameter D_f (m)
1	0.330	2.362E-004	0.351	2.351E-004
2	0.418	2.346E-004	0.434	2.342E-004
3	0.523	2.396E-004	0.547	2.319E-004
4	0.628	2.407E-004	0.682	2.401E-004
5	0.822	2.318E-004	0.850	2.398E-004

Table 2 Parameters for the permeability estimated by the Kozeny-Carmen solution

FIGURES

(a)

(b)

(c)

Fig. 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

Fig. 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

(a)

(b)

Fig. 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. 4 Tension test on individual coir fibre: (a) Experiment; (b) DEM modelling; (c) Stress-strain relationship by experiment and DEM modelling

(a)

(b)

(c)

Fig. 5 Bending test on individual coir fibre: (a) Experimental model; (b) Fibre cross-section under optical microscope observation; (c) DEM modelling

Fig. 6 Capturing the position of fibre particles in a drain: (a) Cross-section of dense coir fibres under microscope; (b) Fibres modelled in DEM

(a) Dense non-twisted fibres, $n = 0.351$

(d) Dense twisted fibres, $n = 0.330$

(b) Medium non-twisted fibres, $n = 0.682$

(e) Medium twisted fibres, $n = 0.628$

(c) Loose non-twisted fibres, $n = 0.850$

(f) Loose twisted fibres, $n = 0.822$

Fig. 7 Segments of fibre bundles built in DEM with different porous structure: twisted and non-twisted fibres

(a)

(b)

Fig. 8 Meshing fluid domain: (a) Longitudinal discretization; (b) Cross-section of fluid domain with the fluid velocity distribution in relation to fibre particles

Fig. 9 Experimental discharge velocity of fluid flowing through fibre drain over hydraulic gradient

(a)

(b)

Fig. 10 Hydraulic conductivity of coir fibres obtained by: (a) Experimental; and (b) In comparison with the K-C analytical methods

Fig. 11 Variation of parameters over fluid cells: (a) Porosity; and (b) Fluid velocity.

Fig. 12 Hydraulic conductivity predicted by the CFD-DEM approach in comparison with the experimental and analytical methods

(a)

Fluid velocity U_f (m/s)

(b)

Fig. 13 Fluid flowing through different fibrous porous structures: (a) Non-twisted; and (b) Twisted fibres; captured by the CFD-DEM method.