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Thanh Trung Nguyen

University of Wollongong, ttnguyen@uow.edu.au

Buddhima Indraratna

University of Wollongong, indra@uow.edu.au

John Philip Carter

University of Newcastle

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Abstract

Naturally occurring materials such as jute and coir have some favorable engineering characteristics and also degrade over time, so they have increasingly been used in engineering applications in recent years. The efficient way that naturally prefabricated vertical drains made from those materials help accelerate soil consolidation has been shown in previous studies, but they also tend to decompose rapidly in adverse environments, where cellulose-degrading bacteria cause a serious deterioration of their favorable drainage properties. This study presents a laboratory investigation into the biodegradation of prefabricated vertical jute drains in saturated soft soils, where the tensile strength of jute and coir fibers and the discharge capacity of drains decrease in response to different environments. Micro-observation also shows a transformation of the jute fibers and destruction of the drain structure due to biodegradation. DNA extraction and sequencing techniques to determine the microbial properties of these decayed fibers indicate that bacteria such as species of the genera *Clostridium* and *Bacillus* can cause rapid decomposition of cellulose-based material (i.e., jute), whereas other organic matter-consuming microbes such as sulfate-reducing bacteria do not directly contribute to the biodegradation of jute. In response, an analytical approach that incorporates various forms of drain discharge capacity over time is proposed to predict soil consolidation. The results indicate there is considerable deviation in dissipating the excess pore pressure when the drain degrades in different ways.

Disciplines

Engineering | Science and Technology Studies

Publication Details

Nguyen, T. Trung., Indraratna, B. & Carter, J. (2018). Laboratory investigation into biodegradation of jute drains with implications for field behavior. *Journal of Geotechnical and Geoenvironmental Engineering*, 144 (6), 04018026-1-04018026-15.

LABORATORY INVESTIGATION INTO BIODEGRADATION OF JUTE DRAINS WITH IMPLICATIONS FOR FIELD BEHAVIOUR

Thanh Trung Nguyen

PhD student,

Centre for Geomechanics and Railway Engineering, University of Wollongong,
Wollongong City, NSW 2522, Australia

Buddhima Indraratna¹

BSc (Hons., Lond.), MSc (Lond.), DIC, PhD (Alberta), FTSE, FIEAust., FASCE, FGS

Distinguished Professor of Civil Engineering,

Faculty of Engineering and Information Sciences,

Director, Centre for Geomechanics and Railway Engineering, University of Wollongong,
Wollongong City, NSW 2522, Australia

John Carter

Emeritus Professor, Faculty of Engineering and Built Environment,
University of Newcastle, Callaghan, NSW, 2308, Australia

Words: 8506

Figures: 18

Submitted to: Journal of Geotechnical and Geoenvironmental Engineering ASCE

¹Corresponding author: Buddhima Indraratna (e-mail: indra@uow.edu.au)

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Abstract

Naturally occurring materials such as jute and coir have some favourable engineering characteristics and also degrade over time, so they have increasingly been used in engineering applications in recent years. The efficient way that naturally prefabricated vertical drains (NPVDs) made from those materials help accelerate soil consolidation has been shown in previous studies, but they also tend to decompose rapidly in adverse environments where cellulose degrading bacteria cause a serious deterioration of their favourable drainage properties. This study presents a laboratory investigation into the biodegradation of prefabricated vertical jute drains (PVJDs or jute drains) in saturated soft soils, where the tensile strength of jute and coir fibres and the discharge capacity of drains decrease in response to different environments. Micro-observation also shows a transformation of the jute fibres and destruction of the drain structure due to biodegradation. DNA extraction and sequencing techniques to determine the microbial properties of these decayed fibres indicate that bacteria such as species of the genera *Clostridium* and *Bacillus* can cause a rapid decomposing of the cellulose-based material (i.e., jute), while other organic matter consuming microbes such as sulphate reducing bacteria do not directly contribute to the biodegradation of jute. In response, an analytical approach that incorporates various forms of drain discharge capacity over time is proposed to predict soil consolidation. The results indicate there is a considerable deviation in dissipating the excess pore pressure when the drain degrades in different ways.

Keywords: natural prefabricated vertical drains; consolidation; natural fibres; biodegradation; discharge capacity.

25 **Introduction**

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

44 While raw natural fibres such as jute and coir can be used to make NPVDs which are
45 normally band-shaped with a number of coir cores wrapped by layers of jute geotextiles (Fig.
46 1a), the straw which is a sub-product of rice fields and very popular in Asian countries is used
47 to create circular drains, as Kim and Cho (2008) describe. This study shows that straw fibre
48 drains have a lower discharge capacity than jute fibre drains but they can still discharge
49 excess pore pressure at an acceptable rate. Jute and coir are the most commonly used

50 materials to manufacture drains because they have distinct engineering characteristics such as
51 durability and high hydraulic conductivity, and are also abundant in many developing
52 countries where the demand for ground improvement is often high. Jute has more than 80%
53 cellulose and only around 12% lignin (Som et al. 2009), making the fibre less durable than
54 coir which has approximately 40% lignin and 43% cellulose (Gupta 2011). Those chemical
55 features also indicate that the biodegradation of jute depends primarily on the decomposition
56 of cellulose, while lignin plays a key role in the decomposition of coir.

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

73 Indraratna et al. (2016) have evaluated the effect that the biodegradation of NPVDs
74 can have on the consolidation of soil by considering an exponential reduction in the discharge

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

84 **Laboratory investigation into the biodegradation of NPVDs**

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

96 **Experimental scheme**

97 Clay soil was collected from 1.5 to 1.8 m deep layers at the National Soft Soil Field
98 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. 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 and discharge capacity tests to determine whether or not they had degraded. The acidity (pH) and ORP of the media were noted respectively.

Tension tests on fibre drains

Tensile strength of fibre drains was measured over time to evaluate how different environments had influenced on their engineering properties. These tension tests were carried out on the complete drain and individual fibres (coir and jute) extracted from the drain (Fig. 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, variation 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 μm while coir fibre was much larger and its diameter varied from 109 to 512 μm . 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).

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 extracted (Fig. 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. 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.

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). 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).

Fibres with surrounding soil particles were extracted from the containers (Fig. 3a) 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); 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 with quantitative data 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.

Discussion of experimental results

Tensile strength of fibre drains

Variations in tensile strength of jute and coir fibres subjected to different soft soil conditions over time is shown in Fig. 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 has a faster reduction in tensile strength 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 reduction curves clearly deviated after this period. Soil 1 has 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 loses 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.

The results of a tension test on fibres located 5 cm deep in soil 1 are shown as the dashed curve in Fig. 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 reduction in tensile strength at different depths in the same soil. These results also show that the decrease in tensile strength of jute only becomes apparent after around 70 days in saturated soil.

Unlike the severe deterioration of jute described above, coir does not show significant reduction in its tensile strength (Fig. 5b). In fact it retains more than 80% its original tensile strength after nearly 600 days and there is no significant deviation in the reduction curves of fibres exposed to different saturated soils, which indicates that coir resists degradation far

better than jute.

Fig. 5b shows the reduction in tensile strength of the whole drain which includes both jute and coir fibres in complete form (Fig. 1a); 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 tensile strength of jute fibres had decreased so much when losing nearly 85% their initial tensile strength (Fig. 5a), thus making the overall strength rely mainly on the strength of the coconut cores which could still maintain significantly their strength, 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. 6a. 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 m³/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 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 m³/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 m³/day under the same confinement as reported in previous studies (Jang et al. 2001; Asha and Mandal 2012).

The reduction in discharge capacity of drains buried in soil 2 and 3 is not significant as Fig. 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 m³/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 m³/day at 180 days to 0.021 m³/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 m³/day.

The variation curve in discharge capacity of drains (Fig. 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. 6b).

Further observation on jute fibres under a microscope after 520 days (Fig. 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 (Fig. 7a), which can reduce the porosity and discharge capacity 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 a 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. 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.

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 addressed and shown in Fig. 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.

The profiles of microorganisms in 3 media at phylum level (a genomic analysis after 630 days at 40 cm depth) are shown in Fig. 10, which indicates almost the same phylum-levelled bacteria but with different contributions to the media. Note that these bacteria (e.g., the phyla Firmicute and Proteobacteria) are generally the most dominant microbes found in soil (Fierer et al. 2007; Berg et al. 2012). The phylum Firmicute 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.

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. 11, where acidity in the medium makes a large contribution to the microbial properties. The Firmincutes 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 Firmincutes found in soil 1 at 40 cm depth (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 shares 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. 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 Chang (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.

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. 12) as usually assumed in conventional approaches (Barron 1948; Hansbo 1981; Indraratna et al. 2005; Rujikiatkamjorn and Indraratna 2006), 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. 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.

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:

$$\frac{u(t)}{u_o} = \exp\left(-\int_0^t \frac{1}{f(t)} dt\right) \quad [1]$$

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

$$f(t) = \chi\left(\mu_{n,s} + \frac{\lambda}{q_w(t)}\right) \quad [2]$$

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:

$$\begin{aligned} \mu_{n,s} = & \frac{n^2}{n^2 - 1} \left[\ln\left(\frac{n}{s}\right) + \frac{k_h}{k_s} \ln(s) - \frac{3}{4} \right] + \frac{s^2}{n^2 - 1} \left[1 - \frac{s^2}{4n^2} \right] \\ & + \frac{k_h}{k_s} \left(\frac{1}{n^2 - 1} \right) \left[\frac{s^4 - 1}{4n^2} - s^2 + 1 \right] \end{aligned} \quad [3]$$

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. [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:

$$q_w(t) = q_{wo} e^{-\omega t} \quad [4]$$

where ω is the decay coefficient and q_{wo} is the initial discharge capacity of the drain.

Substituting Eq. [4] in Eq. [1] and integrating yield:

$$\frac{u(t)}{u_o} = \exp \left[\frac{-8T_{h,a}}{\mu_{n,s,a}} + \frac{1}{\chi_a \mu_{n,s,a} \omega} \ln \left(\frac{\frac{\mu_{n,s,a}}{\mu_{qo,a}} + e^{\omega t}}{\frac{\mu_{n,s,a}}{\mu_{qo,a}} + 1} \right) \right] \quad [5]$$

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 (Fig. 5 and Fig. 6), 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, and loading process.

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.

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. 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. 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. 6a) which is composed of different degradation forms over time. Therefore, in lieu of the exponential form

of Equation [4], a general polynomial degradation form that includes convex, concave and linear degradation curves, is considered as follows:

$$q_w(t) = q_{wo}(1 - at^b) \quad [6]$$

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. [6] into Eq. [1] and re-arranging yield:

$$\frac{u(t)}{u_o} = \exp \left\{ - \int_0^t \frac{dt}{\chi \left[\mu_{n,s} + \frac{\chi}{q_{wo}(1 - at^b)} \right]} \right\} \quad [7]$$

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

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

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

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

$$\frac{u(t)}{u_o} = \exp \left\{ \frac{-8T_h}{\mu_{n,s}} + \frac{\mu_{qo}}{2\chi\mu_{n,s}\sqrt{\mu\mu_{n,s}a}} [\ln(\sqrt{\mu} + \sqrt{\mu_{n,s}at}) - \ln(\sqrt{\mu} - \sqrt{\mu_{n,s}at})] \right\} \quad [9]$$

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

$$\frac{u(t)}{u_o} = \exp \left[\frac{-8T_h}{\mu_{n,s}} - \ln \left(1 - \frac{\mu_{n,s}aq_{wo}t}{(\mu_{n,s}q_{wo} + \lambda)} \right) \left(\frac{\lambda}{\chi\mu_{n,s}^2aq_{wo}} \right) \right] \quad [10]$$

500 In the above, T_h is the time factor for horizontal drainage. $\mu = \mu_{qo} + \mu_{n,s}$ where $\mu_{qo} =$
 501 $(2\pi k_h l^2)/(3q_{wo})$ represents the discharge capacity of the drain at its initial stage. By
 502 providing these solutions for different orders of polynomial degradation curves, the complex
 503 behaviour associated with the reasons a and c as discussed earlier can then be captured in the
 504 revised model.

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

$$\lim_{a \rightarrow 0} \left\{ \ln \left(1 - \frac{\mu_{n,s}aq_{wo}t}{(\mu_{n,s}q_{wo} + \lambda)} \right) \left(\frac{\lambda}{\chi\mu_{n,s}^2aq_{wo}} \right) \right\} = \frac{\mu_{qo}t}{\chi\mu_{n,s}(\mu_{n,s} + \mu_{qo})} \quad [11]$$

508 Replacing Eq. [11] into Eq. [10] and re-arranging the result in Hansbo's solution, that is:

$$\frac{u(t)}{u_o} = \exp \left(\frac{-8T_h}{\mu} \right) \quad [12]$$

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

$$u(t) = - \sum_{i=1}^n u_{0i} \exp \int_{t_{i0}}^{t_{ij}} \frac{1}{f_i(t)} dt \quad [13]$$

where $f_i(t)$ is the function $f(t)$ shown in Eq. [2] in stage i , where the reduction of the discharge capacity is described by the function $q_{wi}(t)$ from t_{i0} to t_{ij} . u_{0i} is the initial excess pore pressure of stage i . For different forms of $q_{wi}(t)$, 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.

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 $0.004 \text{ m}^2/\text{year}$. 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 $9 \times 10^{-10} \text{ m/s}$ is adopted. An initial discharge capacity of $0.43 \text{ m}^3/\text{day}$ was obtained by carrying out a discharge capacity test on a non-degraded PVJD.

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. 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. 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. 14. In this investigation (Fig. 14a), different reduction behaviours of the discharge capacity are assumed in addition to the conventional approach (constant q_w), as follows:

(c.1) An exponential degradation with $\omega = 0.008 \text{ day}^{-1}$ occurs immediately after the drain is

559 installed (no delay time).

560 (c.2) An initial delay (intact) period of 70 days where q_w remains constant is followed by an
561 exponential degradation with $\omega = 0.0089 \text{ day}^{-1}$ for the rest of the investigation period.

562 (c.3) An initial delay period of 20 days is followed by a concave polynomial ($a = 2 \times 10^{-5}$
563 day^{-2} and $b = 2$) and this is followed by an exponential degradation with $\omega = 0.00913$
564 day^{-1} . Compared to case (c.2), a transition period of 80 days (with polynomial
565 degradation) is added.

566 Note that these degradation curves all reach the same final level of drain discharge capacity.
567 Although the discharge capacity test in this study has shown an intact period from 100 to 150
568 days, Kim and Cho (2008) presents an earlier start of the reduction through their laboratory
569 test, indicating a complex reduction behaviour in discharge capacity of natural fibre drains.
570 This section hence assumes an intact period less than 100 days to demonstrate how the
571 analytical model can capture the corresponding soil behaviour. Case (c.1) represents a single
572 form of degradation (exponential) while cases (c.2) and (c.3) show a combination of multiple
573 forms of q_w degradation over time, which is probably more realistic. The consolidation of the
574 soil in case (c.1) is predicted by Eq. [5] for the purely exponential degradation of the drain,
575 whereas for the multi-form degradation, Eq. [13], incorporating solutions for conventional,
576 polynomial ($b = 2$) and exponential degradation, is used.

577 Fig. 14b shows how the consolidation induced by a single form differs from one
578 induced by a multiple-form of degradation. Case (c.1) has the earliest degradation that results
579 in the highest residual excess pore pressure after 500 days while the combined reduction
580 forms, i.e., cases (c.2) and (c.3), which have q_w decreasing after an initial delay stage, do not
581 obstruct the dissipation of excess pore pressure very much. Case (c.2) having the initial 70
582 days without any degradation, followed by an exponential reduction, has the consolidation
583 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 ($\omega = 0.00913 \text{ day}^{-1}$).

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.

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, reductions in the tensile strength and discharge capacity of fibre drains were 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.

1. Coir having a major component of lignin 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.
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 m³/day to 0.05 and 0.025 m³/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.

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. 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.

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.

632 **Acknowledgements**

633 The authors acknowledge the National Jute Board of India and the Australia Research
634 Council for funding this research. The genomic analyses were carried out in the Australian
635 Genome Research Faculty (AGRF). Microscopic observation on the samples was carried out
636 in the Australian Institute of Innovative Materials (AIIM), University of Wollongong. The 1st
637 author's PhD scholarship was sponsored by the Australia Endeavour Scheme.

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FIGURES

a) Structure of prefabricated vertical jute drain

b) Drain insertion

c) pH measurement

Fig. 1 PVJD sample inserted into soft clay and pH measurement

Fig. 2 Tension test on: (a) the whole drain; and (b) individual fibre

a) Schematics of discharge capacity test

b) Drain on pedestal in the test

c) Drain being confined

Fig. 3 Discharge capacity test: a) schematic view; b) drain extracted from soil and wrapped by membrane; and c) drain being confined by cell pressure.

Fig. 4 DNA analysis for decayed fibres: a) fibres extracted from saturated soil; b) fibres in DNA extraction process

a) Individual jute and coir fibres

b) Complete drains

Fig. 5 Reduction in tensile strength: a) individual fibres: b) complete drains

a)

Dark compound built around drains in soil 01

Jute filter broken after 520 days in soil 1

b)

Fig. 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.

Fig. 7 Degradation of jute under micro-observation: a) undisturbed condition; and b) after washing

a) Soil/container 1

b) Soil/container 2

c) Soil/container 3

Fig. 8 The surface of soils after 520 days: a) soil 1; b) soil 2; and c) soil 3

a) pH variation

b) ORP variation

Fig. 9 pH and ORP variations over time: a) pH and b) ORP

Fig. 10 Bacterial profile at phylum level of soils

Fig. 11 Variation of phylum levelled bacteria over different pH of the medium

Fig. 12 Degradation of NPVDs in relation to consolidation process of soil

Fig. 13 Different degradation forms of $q_w(t)$: a) discharge capacity; and b) corresponding dissipation of excess pore pressure.

Fig. 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

APPENDIX A: Microbial Trees of Decayed Fibres Buried in Different Soils

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)