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Influence of soil clogging on the performance of jute fibre drains installed in Ballina clay

T. T. Nguyen & B. Indraratna
Centre for Geomechanics and Railway Engineering, University of Wollongong, Australia

J.P. Carter
ARC Centre for Geotechnical Science and Engineering, University of Newcastle, Australia

ABSTRACT: Biodegradable prefabricated vertical drains (BPVD) made from naturally occurring materials such as jute and coconut (coir) fibre not only have favourable engineering characteristics but also not detrimental to the natural environment thanks to their biodegradability. Although the use of these natural fibre drains has been proposed for several decades, their application is still very limited. One of major reasons for this is because they are usually composed of individual fibres with large openings which can trap fine soils while discharging pore pressure, consequently reducing the hydraulic conductivity of the drain. This study therefore aims to clarify how soil can clog and damage the porous nature and hydraulic properties of fibre drains through an experimental scheme. A typical natural fibre drain composed of a jute sheath and coconut core was adopted in this investigation. A series of discharge capacity tests, in which the drain was confined by soft clay, were conducted. The drain was then subjected to a post-analysis process using micro-CT scanning to identify how the fine soil has penetrated into the drain and whether this has degraded the discharge capacity of the drain. The results indicate that the current drains can resist well soil clogging due to an initial confining pressure of 50 kPa but the drain discharge capacity can decrease considerably if a higher initial confining pressure, i.e., 100 kPa, is applied.

1 INTRODUCTION

Environmentally friendly solutions are desirable for any engineering discipline, particularly in the current era of global warming with its associated environmental issues. This is why considerable effort has been made in recent decades to widen the application of naturally occurring materials in geotechnical engineering. Biodegradable prefabricated vertical drains (BPVDs) made from natural fibres derived from jute and coconut not only benefit the natural environment but also have preferable engineering characteristics, including high discharge capacity and durability, which is why they have received significant attention in recent years (Asha and Mandal 2012; Indraratna et al. 2016; Nguyen and Indraratna 2017; Mirzababaei et al. 2018). Despite these promising aspects, their application has been limited until very recently because their engineering properties have not been well understood. For example, these drains usually have large pores created by the individual fibres, providing the potential to trap soil particles and subsequently reducing their discharge capacity. How significant this reduction is, and whether it can affect soil consolidation, have not been clarified properly. This paper aims to investigate the influence that soil clogging can have on the discharge capacity of BPVDs through a laboratory testing method.

2 EXPERIMENTAL INVESTIGATION

2.1 *Characteristics of jute fibre drains*

Generally a BPVD is made by arranging individual natural fibres in a certain format that can include either circular or banded shapes. Jute and coconut are the most preferred fibres used to fabricate these drains, which is why they are usually named as natural fibre drains or jute fibre drains. In the current study, the behaviour of a band-shaped BPVD, which includes 4 coconut (coir) cores wrapped by a jute sheath, is studied (Figure 1).

While coconut cores are used to shape and strengthen the drain, the jute geotextile acts as an external filter to maintain the internal porous system of the BPVD. Figure 1 shows the structure of the drain used in the current study, as identified from micro-CT scanning and 3 dimensional reconstruction.

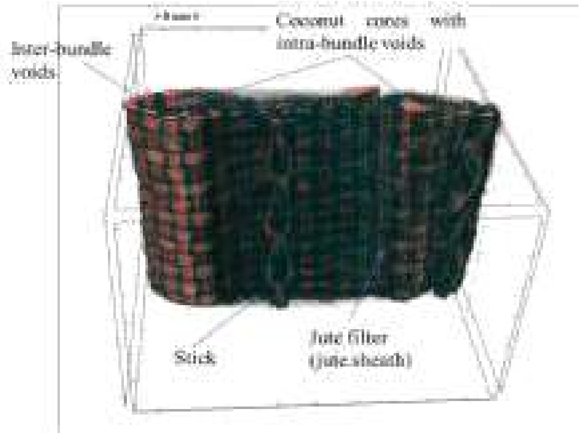


Figure 1 Jute BPVD under micro-CT scanning

It is interesting to note that the drain porosity is composed of two types of voids; namely the inter-bundle and intra-bundle voids (Figure 1). Intra-bundle void means the space allocated within a fibre bundle; this includes voids between single fibres making the jute and coconut bundles. Inter-bundle voids are those distributed between different bundles. Because of the differences in structure between these two void types, they respond differently to confinement, which is explained in detail in the following sections.

Table 1 Physical properties of jute BPVD and polymeric PPVD

Parameters	BPVD	PPVD
Dry unit weight (g/m)	195	66
Tensile strength (kN)	3.24	2.7
Apparent opening size (AOS) of filter (m)	180	< 75
Thickness (mm)	7.71	3.1
Width (mm)	98.15	99

Table 1 summarises the fundamental details of the drains. Compared to conventional polymeric PVDs (PPVDs), the current BPVD is thicker and heavier. The tensile strength of 3.24 kN satisfies the installation requirement in the field (i.e., approximately 0.5 kN).

2.2 *Experimental scheme*

An experimental scheme was established to evaluate the influence of soil clogging on the discharge capacity of the biodegradable drains in comparison with conventional polymeric PVDs (PPVDs). This included 3 stages: (*i*) confining the clay soil around the drain to mimic the drain-soil interaction which occurs in the field; (*ii*) measuring the discharge capacity of the drain after being confined; (*iii*) implementing a post-processing to evaluate the influence of soil clogging on the porous properties of the drain. Details of these steps are described as follows.

(*i*) Soil-drain confinement: a natural clay soil, obtained at 1.5-2 m depth at Ballina, NSW was used in this study. It is worth noting that the Ballina field site was where the first pilot scale project using BPVDs (i.e., jute fibre drains) to improve soft soil was carried out in Australia (Pineda et al. 2016; Nguyen et al. 2018). Several key parameters of this soil are shown in Table 2. The natural soil with a water content (w) of 83.5% was then mixed with fresh water to achieve a reconstituted soil having w above the soil liquid limit, i.e., approximately 95%. This reconstituted soil was then placed into a large cylindrical membrane with a BPVD positioned in the middle. This whole soil-drain set was established in a triaxial cell, as shown in Figure 2. A confining pressure (p_c) was generated on the soil-drain sample via controlling the cell pressure, noting that pore water was free to discharge through the two ends of the drain. Two loading schemes were considered: (1) the confining pressure was increased in stages from 10 to 50, 100 and 200 kPa; and (2) a larger initial increment was made, i.e., from 10 kPa to 100 kPa. This range of p_c mimicked the usual confining pressures acting on PVDs in the field under surcharge. For example, considering Ballina soil under a 10 m high embankment with a unit weight of 19 kN/m^3, would result in a value of p_c of approximately 100 kPa. By carrying out this process, the soil was able to interact with the drain under controlled con-fining pressure.

Table 2 Properties of Ballina clay

Soil parameters	Value
Natural water content	83.5%
Liquid limit	91%
Plastic limit	33%
Dry density (kg/m^3)	850
pH	6.7

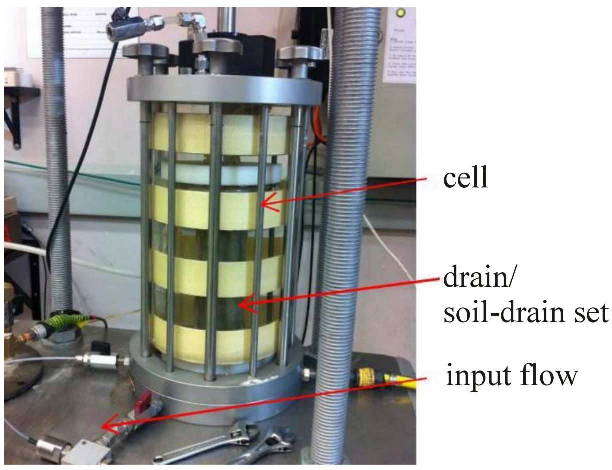


Figure 2 Measuring the discharge capacity of the soil-drain sample under cell confining pressure

(*ii*) Discharge capacity test: after confinement (and full soil consolidation), the soil-drain set was subjected to a discharge capacity test. Flow under a controlled water head was created through the drain. Hydraulic heads were recorded at the inlet and outlet of the drain via manometers. Different water heads (i.e., hydraulic gradients) were applied and the corresponding discharge volume was measured at the outlet of the drain. A hydraulic gradient varying from 0.1 to 1.0 was used. Note that the discharge volume was only taken once steady state flow was reached for each level of hydraulic gradient. Further details of this test can be found in Nguyen et al. (2018). Soil particles washed along with the flow were found during the test, indicating some soil entering and clogging the drain.

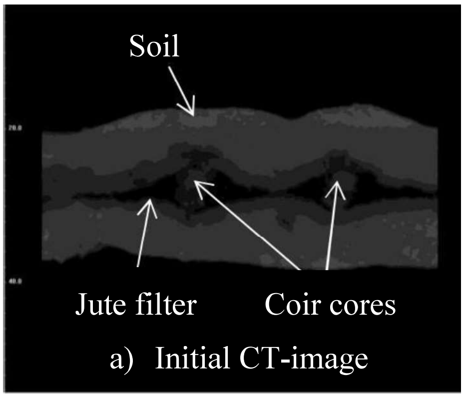
(*iii*) Post-processing of soil-drain sets: following the discharge capacity test was an examination of how soil particles had changed the porous structure of the drain. The sample including the soil and the drain in its intact state was subjected to micro-CT scanning (Figure 3) which was able to explore the interior structure of the sample without disturbance. Unlike other conventional microscopic observations such as optical microscopic scanning, micro-CT scanning can capture the otherwise invisible structural characteristics of a porous object based on the difference in X-ray energy absorption of the different materials making up the object. This enabled the interior of the soil-fibre drain systems to be detailed because of the difference in response of the soil and the natural fibres (jute and coir) to X-ray radiation. Images from the scanning continued to be processed for quantitative information. In this study, a CT scanner named SkyScan 1275 with a voxel resolution of 4 m was used.

Figure 3 Soil-drain sample after confinement being scanned in the micro-CT chamber

2.3 *Image processing*

CT-images were subjected to a series of image analysis techniques to obtain quantitative details which helped understand the porous properties of the drains as well as drain-soil interactions. This procedure included: (1) binarising CT-images which were originally in grey scale; (2) improving the quality of the binary images by conducting image processing techniques such as filtering, de-speckling and watershed, which helped mitigate noise, improve the contrast and identify particles in contact; (3) processing bitwise (logical) techniques to extract desired elements such as soil and fibres which had different grey intensity; (4) conducting 3D analysis for tomographic details such as the volume of components and/or objects. Application of CT-scanning and its subsequent image analysis techniques to geomaterials have shown considerable success in previous studies (Munkholm et al. 2012; Wildenschild and Sheppard 2013). In this study, these techniques were applied using the commercial CTan software with support from an open source program named ImageJ (Schindelin et al. 2015).

Figure 4a shows an example of raw CT-images for a drain-soil system without processing. Soil which has a higher density is present in the brighter areas compared to the jute and coir fibres. After a number of image processing steps, the fibres including the jute and coir were separated (Figure 4b), which enabled the area (and volume in 3D) of the fibres to be calculated. By accumulating a series of consecutive CT-images, the volume of fibres could be obtained. The same procedure was applied to soil, individual fibres as well as bundles of fibres with and without soil to obtain their structural and porous characteristics.



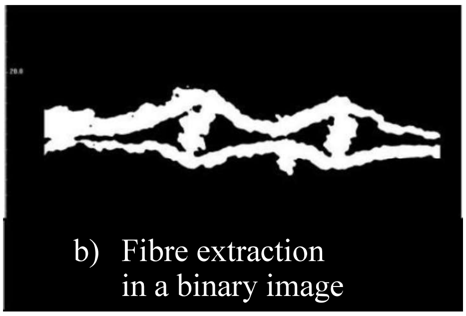


Figure 4 CT-image of drain-soil set and post-processing to extract fibre regions in a binary image

3 RESULTS AND DISCUSSION

3.1 *Discharge capacity*

Figure 5 presents the discharge capacity of the current BPVDs in comparison to other natural fibre drains used in previous studies. Note that the latter tests do not include drains confined by soil. The discharge capacity of the drain used in the current study is about $7\ 10^{-6}$ m^3/s at low confining pressure (i.e., 10 kPa), which agrees well with previous data. The differences in discharge capacity reported by different studies are understandable because of the varying drain structures and testing apparatuses. In all cases the discharge capacity reduces significantly as the confining pressure increases to 50 kPa, indicating considerable reduction in porosity of the drain. However at a higher level of confinement, the reduction in discharge capacity becomes insignificant. In particular when the confining pressure varies from 100 to 200 kPa, the discharge capacity is almost unchanged. This behaviour is somewhat different from some previous studies, e.g., Jang et al. (2001) where their drains still show considerable reduction in discharge capacity at a pressure larger than 100 kPa. This is probably because Jang et al. (2001) used weaker BPVDs than the current study. For example FD2 used by Jang et al. (2001) has only 3 coconut cores which play an important role in resisting confinement, resulting in a more significant reduction in discharge capacity when increasing p_c.

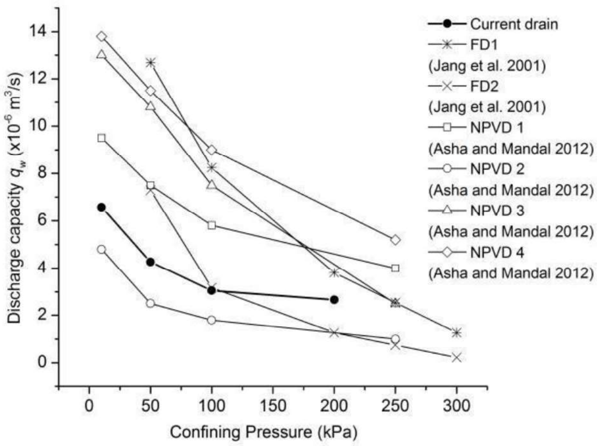


Figure 5 Discharge capacity of the current BPVDs compared to other drains

The discharge capacity q_w of the current BPVDs can satisfy the requirements for assisting soil consolidation to a certain degree, according to Chu et al. (2004). For example, with respect to a treatment depth of 20 m and a soil permeability $k_s = 1\ 10^{-10}$ m/s, the required value of q_w is estimated to be about $2\ 10^{-6}$ m^3/s which is lower than the value of q_w measured in this study. However considering a soil having a higher permeability, i.e., $k_s = 1\ 10^{-9}$ m/s, a larger discharge capacity which exceeds the current measured q_w is needed. But note that soft soil in the field, such as the Ballina clay (Pineda et al. 2016), usually has a value of k_s smaller than $1\ 10^{-10}$ m/s at depths greater than 7 m. Hence proper attention should be paid to drain design when using this type of drain to assist soil consolidation.

3.2 *Effect of soil clogging on discharge capacity*

The discharge capacity measured for the drain confined by soil is shown in Figure 6, together with a comparison to that without soil confinement. The figure indicates the influence that the soil confinement and loading scheme have on the drain discharge capacity. In particular, the discharge capacity decreases from $4.3\ 10^{-6}$ to $4.0\ 10^{-6}$ m^3/s at a value of p_c of 50 kPa due to soil confinement when considering the first loading scheme. This reduction is insignificant. However, a larger initial increment in the confining pressure, i.e., from 10 to 100 kPa, as adopted in the loading scheme 2, results in greater degradation in discharge capacity, viz., a decrease to $2.78\ 10^{-6}$ m^3/s (35% loss) at 100 kPa. Further increase in confining pressure (i.e., from 100 and 200 kPa) does not cause much further reduction in discharge capacity. This probably indicates that a state is reached where additional soil particles cannot be compressed into the drain despite the increasing confining pressure. At low confining pressure the drain performance is not degraded by soil clogging.

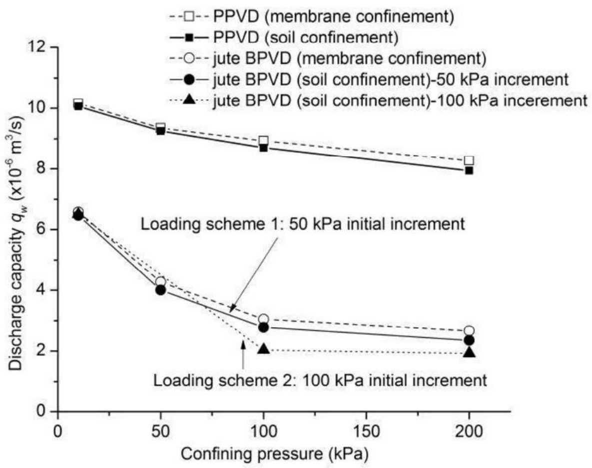


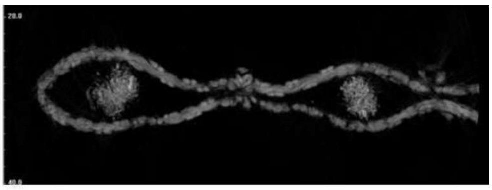
Figure 6 Discharge capacity of the current BPVDs compared to other drains

Figure 6 also compares the discharge capacity of BPVDs with conventional polymeric PVDs (PPVDs). PPVDs generally have much larger discharge capacity, and they are also quite resistant to soil clogging because of their very fine filter (i.e., Apparent Opening Size (AOS) < 75 m). It is interesting to note that while the PPVDs do not have significant reduction in their discharge capacity when p_c increases, BPVDs are very sensitive to confining pressure. This is understandable since BPVDs are composed of individual fibres with large internal pores which are very vulnerable to change when the drains are compressed. Microscopic observations and analyses described in the following sections of this paper will further clarify this aspect of their behaviour.

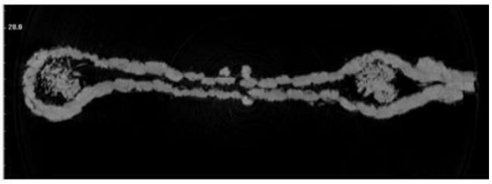
3.3 *Microscopic observations of soil clogging*

Post-processing of CT-images of drain samples after a discharge capacity test revealed that the drain porosity reduced considerably as the confining pressure increased to 50 kPa.

Figure 7 illustrates how the drain volume changed under compression, in this case resulting in approx-imately 22% reduction in the drain porosity. In par-ticular, the drain porosity decreased from 0.86 ini-tially to 0.64 after being confined at 50 kPa. It is interesting that the major reduction is contributed by the decrease in inter-bundle voids, which varied due to fibre rearrangement under confinement. However, the larger confining pressures (i.e., 100 and 200 kPa) only reduced the porosity by about a further 9.4%, making the discharge capacity almost constant at these levels. It is important to note that porosity is the major parameter determining the hydraulic conductivity of fibre drains (Nguyen and Indraratna 2016).



Fresh drain (0 kPa)



Confined drain (50 kPa)

Figure 7 Fresh drain compared to confined drain

Analyses of the drains confined in soil showed that the soil clogged the drains to different degrees depending on the loading scheme. Very little soil entered internal spaces of the drain in the loading scheme 1, while it deposited in those regions considerably in the loading scheme 2, resulting in a larger reduction in porosity. Porosity analysis based on micro CT-scanning showed that the loading scheme 1 in fact caused less than 5% reduction in total porosity of the drain, leading to insignificant changes in drain discharge capacity compared to that without soil confinement. The major contribution to this reduction was the decrease in porosity of the jute bundles making up the drain filter, which was the external layer interacting directly with the soil. The internal voids were almost unchanged by soil confinement in this case. In the loading scheme 2, a significant amount of soil was found within inter-bundle voids because the jute filter could not prevent soil penetrating into these internal regions at the larger initial increment in confining pressure (i.e., 100 kPa compared to 50 kPa in the scheme 1). A larger initial pressure caused more soil penetration because the soil behaved much like a liquid at the beginning of loading (initial water content w = 95 %), while subsequent pressure increases did not lead to much soil clogging as the soil had already been consolidated considerably after the first stage of confinement.

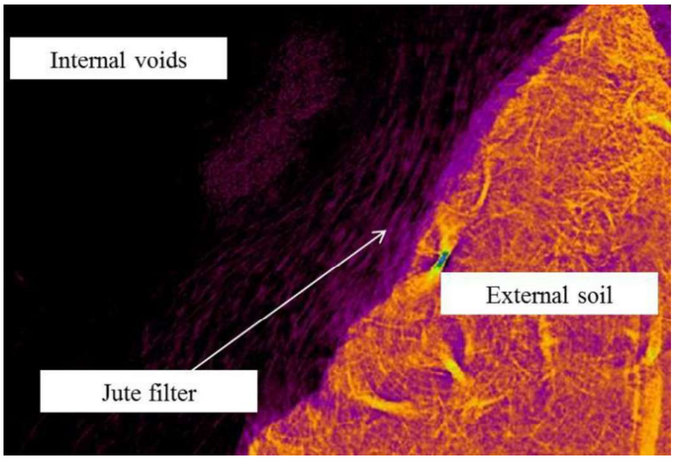


Figure 8 Jute filter-soil interaction after 50 kPa confinement (load scheme 1) examined under micro-CT scanning

4 CONCLUSIONS

The paper has presented an experimental investigation into the influence of soil clogging on the discharge capacity of biodegradable prefabricated vertical drains (BPVDs). A series of image analyses were made after the drain-soil samples were subjected to confinement, discharge capacity testing and micro-CT scanning. The results indicated that the BPVDs (i.e., jute fibre drains) used in the current study could resist soil clogging very well. There was only about 5% of porosity reduction due to soil clogging under loading scheme 1 (i.e., initial increment in confining pressure of 50 kPa), leading to a slight reduction in the drain discharge capacity. More soil was found in the internal-bundle voids when the drains were subjected to loading scheme 2 which had a larger initial increment in pressure. The total porosity in this case decreased about 17%, resulting in a significant reduction in discharge capacity (i.e., 35%). These findings have clarified why jute fibre drains with large openings can still accelerate soil consolidation well compared to conventional synthetic PVDs. However, careful attention should be paid to drain design and potential clogging if a fast increment in the surcharge loading is applied.

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