*Nguyen, T.T., Indraratna, B. and Baral, P. 2020. Biodegradable prefabricated vertical drains: from laboratory to field studies. Geotechnical Engineering Journal of the SEAGS & AGSSEA, 51(2): 39-46.*

# Biodegradable Prefabricated Vertical Drains: from Laboratory to Field Studies

Thanh Trung Nguyen[1], Buddhima Indraratna[2], and Pankaj Baral[3]
[1,2,3]*Faculty of Engineering and Information Sciences,*
*University of Wollongong, Wollongong City, NSW 2522, Australia*
*Corresponding E-mail*: indra@uow.edu.au

**ABSTRACT:** Biodegradable prefabricated vertical drains (BPVDs) made from natural fibres have been in use for several decades to improve soft soil, especially in East and Southeast Asia despite the fact that this type of drain has still not been fully addressed and evaluated. This study presents a series of laboratory tests where a drain made from coconut cores wrapped in Indian jute sheath filters is compared to conventional synthetic prefabricated vertical drains (SPVDs). Discharge volume tests are carried out with and without soil clogging to understand how jute drains can resist soil clogging under increasing confining pressure. Along with these macro-hydraulic tests, the influence that the micro-characteristics of natural fibre drains can have on their hydraulic conductivity is also examined using micro-CT scanning and an optical microscopic to capture the micro-details of these drains. This study shows that the porous structure of BPVDs is much more complex than SPVDs, which causes them to have a lower discharge capacity. Unlike SPVDs, micro-properties also play an important role in the hydraulic properties of BPVDs. A pilot project in soft soil at Ballina, Australia, where BPVDs were installed in parallel to SPVDs, was used to evaluate their performance in assisting soil consolidation considering the biodegradation of natural fibres. The identical performance of these two types of PVDs added further evidence to prove how well BPVDs can facilitate soil consolidation.

**KEYWORDS**:…

## 1. INTRODUCTION

Synthetic prefabricated vertical drains (SPVDs) made from polymer based geomaterials are used extensively over the years (Bergado et al. 1996; Arulrajah et al. 2009; Chu et al. 2009; Indraratna et al. 2019), however, their high resistance to biodegradation puts underground soil and water at risk of disturbance and contamination (Gregory and Andrady 2003; Bläsing and Amelung 2018). The engineering properties of natural fibres, such as jute and coconut, are increasingly being used for a variety of geoengineering projects, such as reinforcing soil (Babu and Vasudevan 2007), separation (Vinod and Minu 2010), and drainage enhancement (Lee et al. 1994; Kim and Cho 2008; Nguyen and Indraratna 2017a). These naturally occurring materials are used to successfully create biodegradable vertical drains (usually abbreviated as either NPVDs or BPVDs) over different regions, especially in countries such as Japan, Korea, Malaysia and Singapore (Lee et al. 1994; Lee et al. 2003; Kim and Cho 2008). While natural fibres are abundant in many developing countries, using them for geotechnical purposes can bring both economic and environmental benefits to local societies.

Previous laboratory investigations (Jang et al. 2001; Asha and Mandal 2012; Nguyen et al. 2018a) show that BPVDs made from jute and coir fibres have enough discharge capacity to accelerate soil consolidation and thus exhibit the same behaviour as conventional SPVDs. However these studies have not addressed the micro-features of BPVDs as well as their effect on the hydraulic properties of drains. For example, how differences in the shape and size of individual fibres can affect the discharge capacity of the whole drain is ignored in most previous studies, in which makes it difficult to design and manufacture these drains. In fact, any changes in the structural characteristics of jute fibre drains (see Figure 1) since their introduction by Lee et al. (1987) more than 30 years ago are insignificant, so they are not used as widely as they could be because they are inefficient to manufacture (Nguyen et al. 2018b). Therefore, the intrinsic link between micro- and macro-hydraulic properties needs urgent clarification.

Although BPVDs were applied in the field with some success (Lee et al. 1994; Lee et al. 2003; Kim and Cho 2008), there is still not enough data to evaluate their performance in a well instrumented pilot test. The question of whether natural fibres, such as jute with its small amount of lignin (Som et al. 2009), can resist biodegradation in saturated estuarine soils, especially in Australia, is still somewhat controversial because the biodegradation of natural fibres varies according to the acidity and biological characteristics of the soil. It is therefore essential to examine the performance of BPVDs in Australian soil conditions to better understand their characteristics and confidently increase their use in practice.

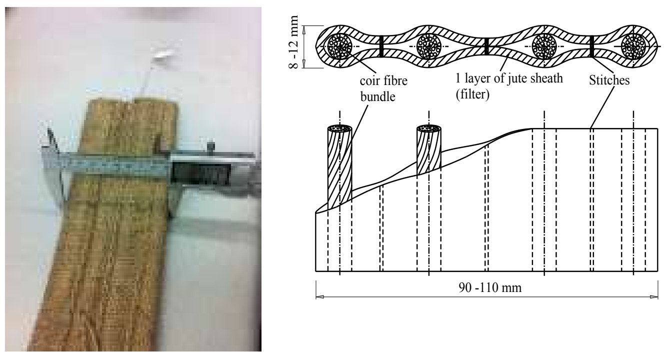



Figure 1 Structural detail of BPVD (jute fibre drains)

This paper presents a comprehensive laboratory and field study evaluation of BPVDs based on discharge volume tests on complete drains and individual fibre bundles. These tests enable a comprehensive understanding of their hydraulic properties from micro- to macro perspectives. The application of BPVDs made from jute and coconut fibres in soft Ballina soil (northern New South Wales, Australia) is also described and discussed in this paper.

## 2. LABORATORY INVESTIGATION INTO THE HYDRAULIC PROPERTIES OF BPVDs

### 2.1 Porous-structural characteristics of BPVDs

For more than 30 years, vertical drains have been made from natural fibres with various structural forms. For example, the first natural fibre drains (Lee et al. 1987; Lee et al. 1994) consist of 4 coconut fibre cores wrapped in 2 layers of jute filter; they were approximately 5 to 10 mm thick and their width varied from 80 to 100 mm. These band-shaped BPVDs have been widely used in later studies and field applications (Jang et al. 2001; Lee et al. 2003; Kim and Cho 2008; Nguyen et al. 2018a). Other forms of BPVDs, such as circular drains composed of inner coconut fibres and external jute filters (Jang et al.

2001); straw drain board (Kim and Cho 2008), and those with internal coir mats (Asha and Mandal 2012), have been also proposed, but with less validation in the field. In this current study, the most common form of BPVDs, i.e., band-shaped drains with 4 coconut cores and 1 layer of jute sheath are used (Figure 1). The apparent opening size (AOS) of the filter is 180 μm and the dry mass over a unit length is 193 g/m.

### 2.1.1 Micro-CT scanning and image analysis techniques

To understand the porous structure of these drains, microscopic observation techniques such as Micro-CT scanning and optical microscope are used. Conventional optical methods cannot capture internal features without disturbing the structure, whereas high resolution Micro-CT scanning provides structural information in detail. Furthermore, Micro-CT scanning enables structural details such as the distribution of porosity and the solid fraction, to be quantified very well. This explains why this technique is widely used to explore the porous characteristics of geomaterials (Taud et al. 2005; Wildenschild and Sheppard 2013; Nguyen and Indraratna 2019). In this study, Micro-CT scanning is implemented on a SkyScan 1275 model with a 4 μm voxel size resolution (SkyScan 1275 2016) that can deliver accurate quantified data. These fibre drain samples were subjected to optical scanning to further support the analysis.

The drain was exposed to an X-ray beam to help characterise its geometrical properties on the basis of the differential energy absorption of coir and jute fibres. The difference in the density of jute, coir fibres, and soil in the fibre-soil composites resulted in CT-scanning images with a distinct grey scale, which helped feature their volumetric fraction. Figure 2 shows how the cross-section of the drain is captured in grey scale and how the 3D coloured drain is re-built using the Feldkamp algorithm for reconstruction (Feldkamp et al. 1984; SkyScan NV 2011). In this investigation, X-ray scanning was applied onto the individual fibre bundles that make up the drain, as well as the complete drain, to ensure the accuracy of the fractional data. An investigation into how varying scanning resolutions can affect the accuracy of volumetric measurement is also made to validate the optical observations (Figure 3). For example, with a scanning resolution larger than 15 μm, the quality of the binary images of coir fibres is poor and result in an almost 11% deviation from the optical images.

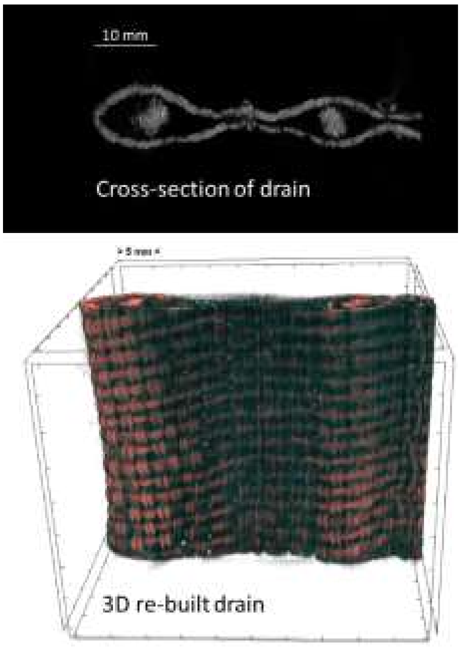
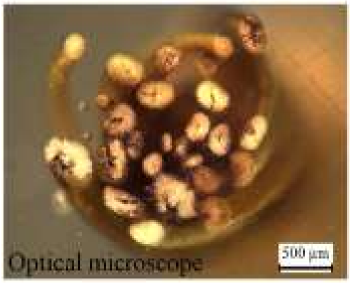
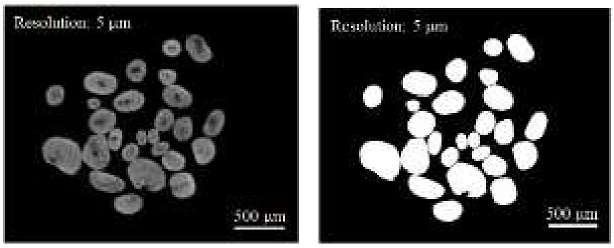



Figure 2 Cross-section and 3D rebuilt drain

A series of image analysis techniques were carried out on scanning products to achieve quantitative data. Original CT and optical scanning images needed transforming into a binary format in which different components of the sample are distinguished from each other in black and white. A threshold process that includes local and global algorithms was applied to binarized images. To improve the quality of images, a number of techniques such as filtering and de-speckling were used. The watershed process was also applied onto the binary images to separate the contact fibres before carrying out a fractional analysis. Note that the 3D volumetric data of an object is actually generated by combining various consecutive slide images over its longitudinal axis.




a) Coir fibres under optical observation




b) Coir fibres under CT-scanning (left) and its binary form (right)

Figure 3 Validation of Micro-CT scanning to optical microscope

### 2.1.2 Porous structural details of BPVDs

The investigation using micro-scanning and image analyses reveals there are two types of voids in the fibre drains. The first source is the intra-bundle voids, which make up the internal space within a single fibre bundle, and the second source is the inter-bundle voids in the space between different bundles. Note that a fibre drain is actually a combination of individual bundles of fibres in a certain range. The intra-bundle void resist the confining stress much better than the inter-bundle void because the fibre bundles are made by twisting individual fibres together, hence their tight and complex porous system. A fractional analysis based on CT-scanning shows that the porosity of the intra-bundle voids accounts for approximately 38% of the overall porosity of a complete drain at zero confinement, but as the confining stress increases, this porosity rises to about 52% due to a large reduction in the volume of inter-bundle voids. This also indicates how the inter-bundle void is sensitive to confinement.

In comparison with conventional SPVDs, BPVDs have almost the same overall porosity, i.e., approximately 0.8 in a fresh condition (Figure 4), but under increasing confining stress, the porosity in BPVDs decreases much faster than SPVDs; for example, it reduces to almost 0.6 when the confining stress increases to 50 kPa. However, this reduction in porosity becomes insignificant as the confining stress continues to increase; this indicates that the fibres cannot re-arrange themselves anymore. Since the porous characteristics of these drains affect their discharge capacity, it will be discussed in the following section. Finally, the analysis based on Micro-CT scanning also indicates that BPVDs have a much larger surface area, i.e., approximately 6.32 m2 per unit length generated by a large number of the individual fibres inside these drains whereas SPVDs consist of plastic cores with only a 0.33 m2 surface area.

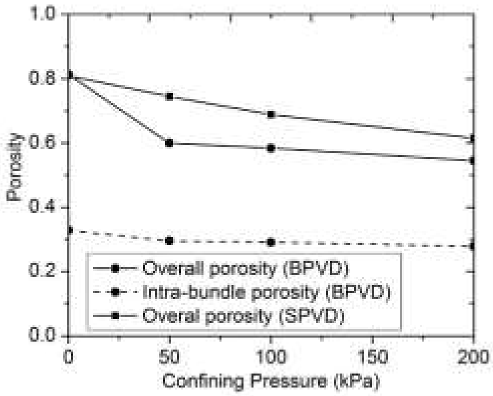
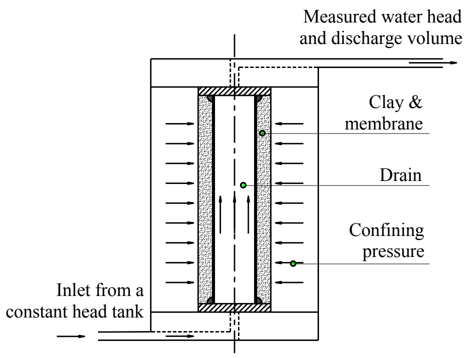



Figure 4 Porosity varies over increasing confining stress (BPVD in comparison with SPVD)

## 2.2 Discharge volume of BPVDs with and without soil clogging

### 2.2.1 Discharge volume test

A discharge volume test is often used to measure the discharge volume of PVDs in the laboratory, but the drain-soil interaction where soil clogs a drain due to confinement is usually ignored for simplicity (ASTM D4716 2008; Asha and Mandal 2012; Bo et al. 2016). In this study, however, a discharge volume test that includes soil clogging was designed and established. The sample drain was inserted into slurry made by mixing Ballina clay with water to approximately 98% water content, which was then contained in a circular membrane before seating it into a test cell (Figure 5).




a) Schematic view of discharge volume test

b) Drain being confined after testing

Figure 5 Discharge volume test on drain (with and without soil)

A flow under controlled input water head was then generated at the bottom end of the sample while the output water head and discharge volume were measured over time. The hydraulic gradient (i) of the flow is then estimated with respect to the difference in water head between the inlet the outlet, and the length of the sample. In this test the confining stress on the drain was governed through cell pressure, in this instance confining stress of 10, 50, 100 and 200 kPa were applied to determine how the confining stress affects the discharge volume. These chosen confining stress reflect the staged construction of an embankment in the field where the surcharge gradually increases (Chu et al. 2009; Rujikiatkamjorn and Indraratna 2009). The confining stress only increases when the soil is fully consolidated, i.e., there is no more discharge water at the outlet of the sample. Discharge volume tests without soil confinement were also carried out in this study.

### 2.2.2 Test results

Figure 6 shows the discharge volume of BPVDs with and without soil confinement; here flow decreased from 6.8 to 4.3 × $10^{-6}$ $m^3/s$ when the confining stress increases to 50 kPa, which matches well the reduction in porosity discussed earlier in the paper. A further increase in confinement does not change the discharge volume significantly. Unlike SPVDs, BPVDs have a much smaller discharge volume at the same confining stress despite having the same porosity. This is because fibre drains have a much larger surface area which is actually the fluid-fibre contact area whenever fluid flows through the drains. A previous study (Nguyen and Indraratna 2017b) indicate that the larger the fluid-fibre contact area, the larger the flow friction and the smaller the hydraulic conductivity of the medium.

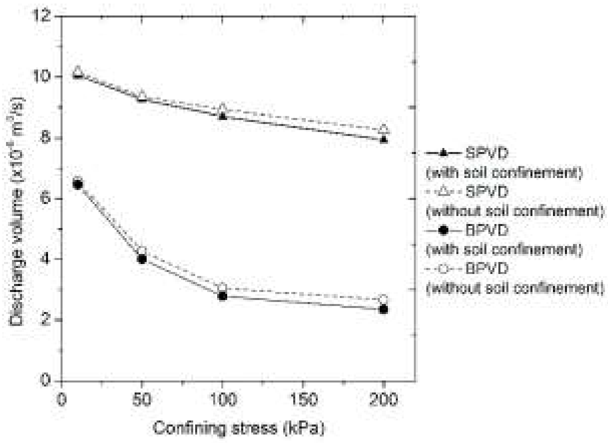



Figure 6 Discharge volume over increasing confining stress

This study also shows that the Ballina clay soil used in the current experimental investigation has almost no influence on the discharge volume of BPVDs and SPVDs. This is understandable because SPVDs have a very fine AOS, i.e., less than 75 µm, as shown in previous studies (Chai and Miura 1999). BPVDs have larger AOS (i.e., 180 µm), however, micro-scanning of the jute filter indicates that soil could not penetrate very far into the drain, therefore, most of the soil clings to the external surface of the filter (Figure 7), and the internal porous system remains intact.

Figure 7 Internal observation under optical-microscope on jute filter and coconut cores indicates no soil clogging BPVDs

### 2.3 Influence of micro-features of fibres on hydraulic properties of BPVDs

#### 2.3.1 Hydraulic test on single bundle of fibres

A hydraulic test at bundle scale (Figure 8) was conducted to measure the hydraulic conductivity of the jute and coir bundles that are used to make BPVDs. It is essential to understand how much the void depositing inside the fibre bundles (intra-bundle void) contribute to the overall discharge volume, and how the micro-features of individual fibres can affect the hydraulic properties of these drains. In this investigation, fibre bundles were placed inside a plastic tube with smooth internal walls to mitigate friction, and like the discharge volume test described in previous sections, flow was generated from one end of the tube to the other. After this test was complete, the bundles were subjected to micro-scanning and analysis to capture their micro-features such as porosity, size, and shape. Fibre bundles were 100 mm long and the internal diameter of the tube was 4 mm.

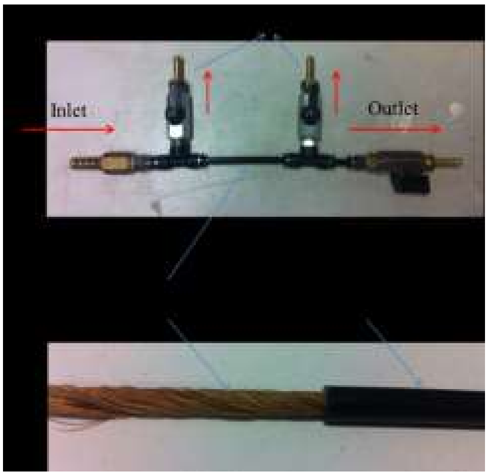



Figure 8 Hydraulic test at bundle (micro) scale

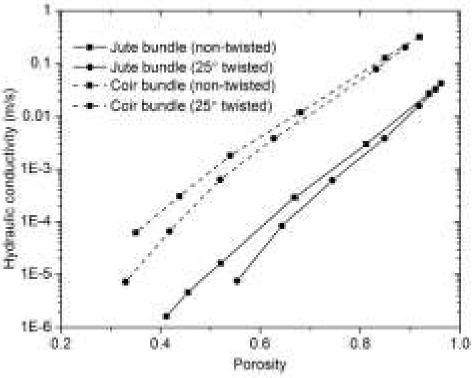
#### 2.3.2 The role of micro-features in hydraulic conductivity of BPVDs

This micro-investigation shows that the diameters of these coir fibres vary from approximately 91 μm to 505 μm, which is much larger than the diameter of the jute fibres (17 to 87 μm). The average diameter of coir is 234 μm whereas jute is almost 42 μm; moreover, the coir fibres are more circular than the jute fibres.

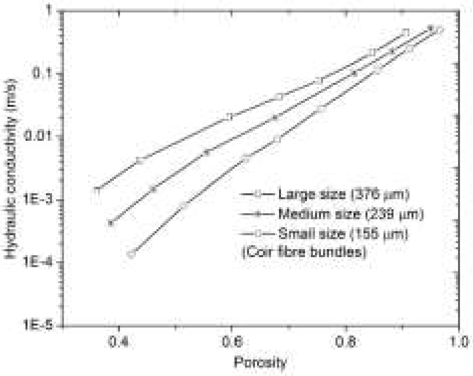
Figure 9 shows the hydraulic conductivity (k) of jute and coir fibres with different porosity (n). Apparently jute fibres have a much lower hydraulic conductivity than coir fibres but with the same porosity. However, the k of jute and coir decreases from 2×10-3 and 7×10-2 m/s, respectively at n = 0.8 to 1×10-5 and 9×10-4 at n = 0.5; which indicates that despite the coir fibres having a smaller volumetric fraction, they can make a large contribution to the drain discharge capacity. At medium to dense packing, i.e., n < 0.5, k reduces more steeply. Moreover, as the fibres are twisted more and more, the hydraulic conductivity decreases as the fluid flow becomes more tortuous; for example, twisting coir fibres by 25° reduces their hydraulic conductivity by a factor of 1.8 at n = 0.6.

The size of fibres has a big influence on hydraulic conductivity, as shown in Figure 9b; essentially, the larger the fibres, the higher the hydraulic conductivity. For example, the k of coir bundles decreases from 2×10-2 m/s to 3×10-3 m/s at n = 0.6 as the mean diameter decreases from 376 to 155 μm. The influence of size is more apparent when the fibre bundles become denser, especially where n < 0.7. This finding clarifies why jute, with the much smaller diameter shown above, has a much lower hydraulic conductivity than coir. The micro-features of fibres must be considered when designing and manufacturing fibre drains.

Note that bio-degradation, which is a unique feature of BPVDs is not examined in this paper due to its complexity, however, further details can be found in other independent studies (Nguyen et al. 2018a). A brief discussion of the biodegradation of BPVDs with reference to a field investigation (i.e., the Ballina project) is presented in the following parts of this current paper.




a) Hydraulic conductivity over porosity of fibre bundles




b) Influence that the size of fibre has on hydraulic conductivity

Figure 9 Hydraulic conductivity of jute and coir bundles making BPVDs (after (Nguyen and Indraratna 2017b)

## 3. Field investigation into the performance of BPVDs

### 3.1 Soft soil condition in Ballina

Ballina (Figure 10) is an important region because it connects two of the largest states of Australia, i.e., New South Wales (NSW) and Queensland (QLD), which is why infrastructure development projects such as the Woolgoolga to Ballina Pacific Highway with 4.5 billion AUDs funded by Australian government in 2015 have taken place in this region.


Figure 10 Location and plan views of trial embankment in Ballina

The soft estuarine soil built up by the Richmond River over a long time has high to extremely high plasticity with low shear strength and high compressibility characteristics. This poses huge challenges to soft soil stabilisation and foundation engineering. This is why the first National Soft Soil Testing Facility (NFTF) was established at Ballina in 2013 (Kelly 2013) as part of Ballina Bypass project, to enhance the understanding of soft soil behaviour in relation to ground improvement techniques, and, thus, increase efficiency and safety in design and construction.

The soft soils at Ballina were characterised in previous investigations (Pineda et al. 2016; Kelly et al. 2017). Generally, there was an approximately 0.2 m thick layer of organic material at the surface followed by 1.0 to 1.3 m thick layer of sandy to clayed silt alluvium soil. The Holocene estuarine soft clay accounts for most of the approximately 9 m thick layer in the Ballina soil profile (Figure 12). This soil has high natural water content, ranging from 80 to 120% about 10 to 15% below less than the liquid limit (LL). Moreover, the plastic limit (PL) is high to very high plasticity, resulting in a PI that ranging from 40 to 70. The dry density is less than 800 kg/m$^3$. Sand was the major component above 2.0 m depth, however, clay particles were dominant at deeper layers, with the soil containing up to about 80% clay-size particles. An approximately 4 m thick layer of sand mixed with clay was found below the Holocene clay making for a transition zone from Holocene clay to the underlying fine sand layer to a depth of 19 m. The properties of these soils are shown in Figure 11.

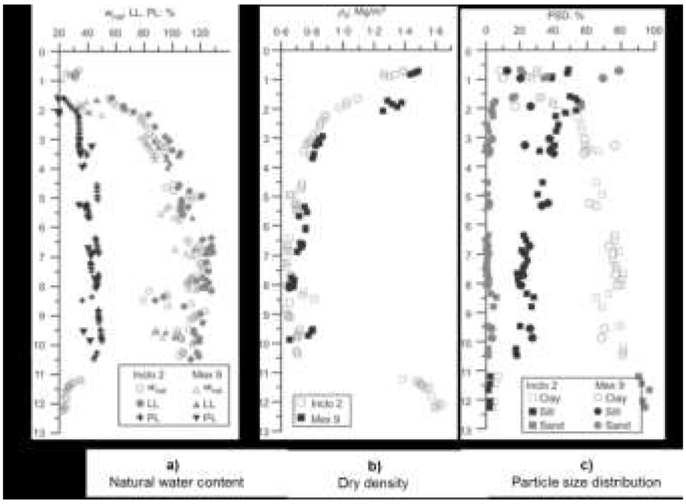



Figure 11 Soil parameters vary over depth (after Kelly et al. 2017)

### 3.2 Soft soil improvement using BPVDs in Ballina

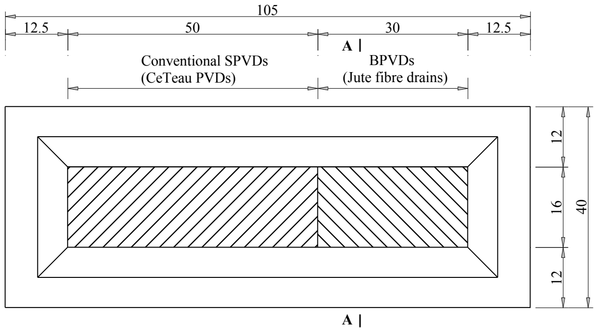
A full-scale trial embankment constructed at Ballina was used to discover how BPVDs work in comparison to conventional SPVDs. In this project, the jute fibre drains described previously and SPVDs (i.e., CeTeau polymer PVDs) were used. The schematic details of this embankment with a typical cross-section at the BPVD treatment zone are shown in Figure 12. An embankment (22 m wide) had a slope of approximately 1.5H:1V, and was almost 80 m long. There were two basic treatment zones, a 50 m long zone for SPVDs and a 30 m long zone for BPVDs. A working platform (about 120 by 50 m) was established initially for site activities. Before installing the drains, a 0.4 m thick sand blanket was placed on the working platform over the footprint (about 105 by 40 m) of the embankment.

The following major steps were carried out in this project:

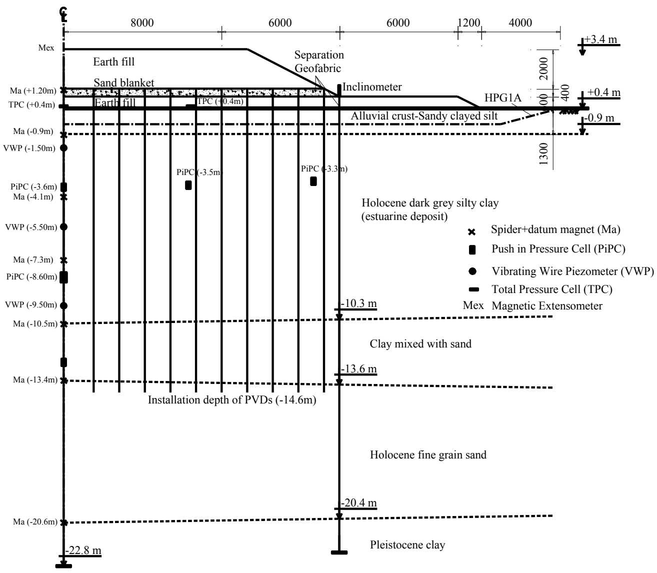
*a)* Site preparation including access roads, levelling, and in-situ testing.

*b)* Installation of instruments. Details of different instruments are given later in this paper.

*c)* A layer of geofabric was used for separation before placing a 0.6 m thick fill over the site to serve as a working platform. Proper compaction and drainage were then carried out.




a) Embankment plan of BPVDs (jute drains) and SPVDs




b) Cross-section A-A in jute fibre drain zone

Figure 12 Plan view and cross-section of embankment

*d)* Thereafter, a 0.4 thick layer of sand was placed on the platform with a layer of geofabric to separate the layers.

*e)* Installation of SPVD and BPVD drains; although the BPVDs were thicker and heavier than the SPVDs, the conventional installation method using a 120 × 60 mm mandrel was found to be applicable for BPVDs.

*f)* Horizontal drainage connecting vertical drains was carried out. In this project, sand blanket and horizontal PVDs were both used in the SPVDs treatment zone.

*g)* The embankment consisted of additional 2 m fill (to a 3m total height over the original ground surface) placed over a second layer of geofabric which covered the sand blanket. The construction post-process included shaping and reinforcement to avoid erosion.

*h)* The embankment was constantly monitored for about 3 years from 2013 to 2016 (Figure 13).

The vertical drains were installed in 1.2 m square spacing pattern to a depth of approximately 14 m (i.e., into the sandy clay but above the sand layer, see Figure 12b) from the ground surface. The installation took place after instrumentation and additional fills (step c and d). A cut-off of 0.3 m from the sand blanket took place after installation reached the target depth. The construction stage associated with surcharge loading over time is shown in Figure 13. Note that it took more than 60 days from beginning of work to construct the platform to completing all the steps. For instance, it took 21 days to install the PVDs and, then, complete the final 2 metre of embankment.

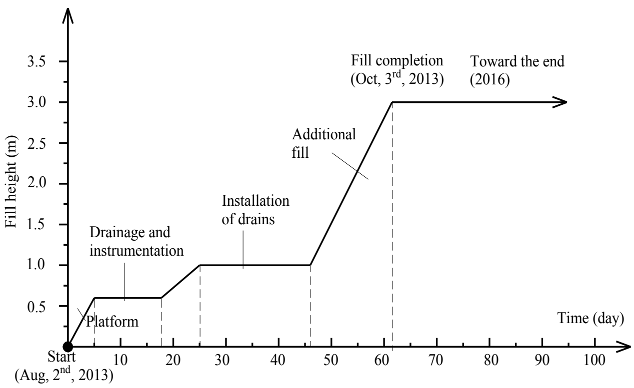



Figure 13 Construction stage with surcharge loading over time

Instrumentation and monitoring is a crucial aspect because it affects the accuracy and decision making of this project. Settlement plates (SPs) were used to record the surface settlement of the ground (e.g., beneath the embankment) and vibrating wireless piezometers (VWPs) were installed at important points (e.g., centre line) over the depth and other positions over space. The hydrostatic profile of the ground (HPG) was recorded by gauges to obtain any variations in the water table during construction and while the PVDs were operational. The VWPs are installed before constructing the platform. Total stress cells (TPCs) were used to measure the total stress imposed by the embankment on the ground, while settlement at different depths (layered settlement) was captured through magnetic extensometers that contained plate, spider, and datum type magnets. Inclinometers were installed at the edge of embankment (Figure 12b) to record lateral deformation, but note, in this project, the total horizontal stress was also measured by push-in stress cells (PiPCs). All the sensors and instruments had been calibrated before and after installation. Data from the VWPs, TPCs and PiPCs was obtained electrically through an on-site data logger system, whereas the SPs, Mex, HPG, and inclinometers were read manually every week during construction, and, then, monthly during post-construction. More details of site works and instrumentation can be found in other studies pertaining to this project (Indraratna et al. 2018; Kelly et al. 2018).

### 3.3 Results and discussion

#### 3.3.1 Settlement and corresponding excess pore pressure over Time

Figure 14 shows the settlement and associated excess pore pressure at the centre lines of the SPVDs and BPVDs zones over time; obviously, there are no significant differences between these two types of drains. Settlement rapidly increases before the embankment (i.e., 3 m high fill) is complete because the build-up excess pore pressure which has been generated since the beginning of construction is released by the installation of PVDs. For instance, there is a steep increase in settlement 30 days after the PVDs were installed (Figure 13). In fact, the settlement reached almost 85% of its primary settlement after approximately 300 days. The settlement curve gradually stabilises over time, although it increases slightly between 500 and 800 days, and then continues to increase faster after 800 days; this might indicate a secondary consolidation of the soil. This concept can be supported by considering the dissipation of excess pore pressure, because after 700 days the change in excess water pressure is insignificant, which means the increase in settlement after 800 days shown in Figure 14a is mainly due to secondary compression. There is a slightly higher excess pore pressure induced by SPVDs at the beginning, i.e., 40 kPa at 60 days, but both curves quickly become identical afterwards. The excess pore pressure from the BPVDs becomes smaller than SPVDs after about 700 days while the settlement induced by these two drains is still the same, although there are data missing from 780 to 900 days due to an accidental disconnection of cables in the BPVD site. These deviations are not easy to understand, given the volume of monitoring data, but they could be induced by the degradation of piezometers and drains (i.e., kinking and bending due to large settlement), leading inaccuracy of data, as sometimes reported in the field (Indraratna et al. 2017).

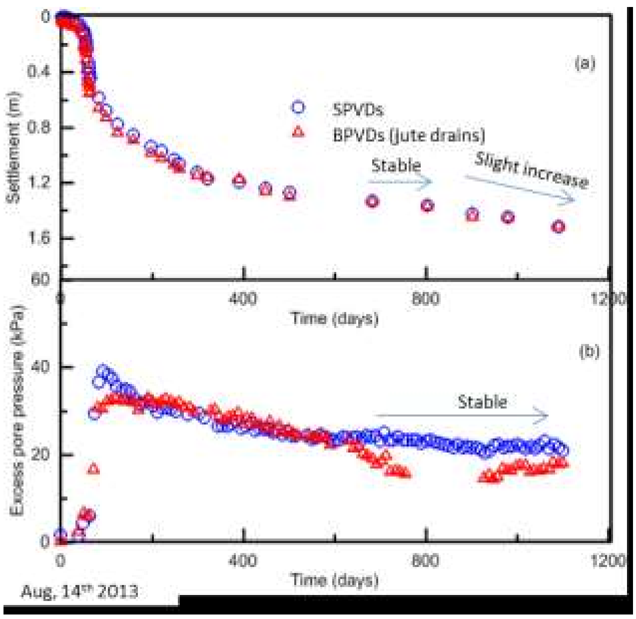



Figure 14 Settlement and corresponding excess pore pressure by BPVDs compared to SPVDs

#### 3.3.2 Lateral deformation

The lateral deformation (inclinometer data) of soil under the embankment after 1088 days of monitoring is shown in Figure 15. Similarly to the settlement described in previous figures, the difference in lateral deformation induced by SPVDs and BPVDs is insignificant, especially at layers deeper than 6 m.

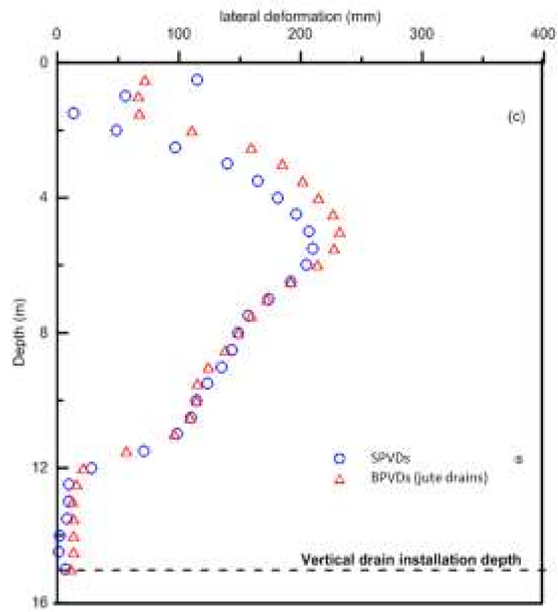



Figure 15 Lateral deformation of soil induced by BPVDs and SPVDs

However, there is a certain gap between the two curves at shallower depths, particularly from 2 to 6 m where the lateral displacement induced by BPVDs is about 210 mm at the depth of 4 m, whereas the SPVDs result in a smaller displacement of 180 mm at the same depth. This discrepancy is probably because BPVDs made from jute fibres are not as stiff as plastic PVDs, in which results in a larger lateral displacement under the same confining stress. Previous laboratory investigations (Jang et al. 2001) indicate that natural fibre drains are more sensitive to deformation (i.e., bending and kinking), and this could result in a much larger lateral deformation of soil reinforced with PVDs. However this deviation could also occur naturally at these two stations without the effect from the difference in stiffness of the two drains. This means that lateral deformation needs further investigation and evaluation. Most of the previous field investigations (Lee et al. 1994; Lee et al. 2003; Kim and Cho 2008) concentrate mainly on settlement and excess pore pressure and ignore lateral deformation.

### 3.3.3 Biodegradation behaviour of BPVDs

Although some previous works (Indraratna et al. 2016; Nguyen et al. 2018a; Nguyen et al. 2018c) indicate that biodegradation can have some influence on the consolidation of soil, there was no evidence of this aspect in this project. The development of settlement and dissipation of excess pore pressure were almost identical, as shown in previous sections, thus indicating there was no significant biodegradation of BPVDs. However, the degradation of BPVDs was investigated in the field about 25 months after they had been installed. A quick pull-out test was made with a crane on a jute drain in the field; the drain broke easily at approximately 0.5 m below the working platform, which indicates a considerable degree of biodegradation. Previous investigations (Nguyen et al. 2018a) show that jute drains are more vulnerable to surface soils where the microorganisms are more active due to the high concentration of oxygen. However, this degradation in tensile strength, especially after 25 months, where primary consolidation had almost been completed (i.e., 99% dissipation of excess pore pressure) had no adverse influence on the consolidation target of this project.

## 4. CONCLUSION

This paper validates the performance of biodegradable natural jute fibre drains after considering laboratory and field evidence. The hydraulic properties and biodegradation aspects are discussed in the paper with the following findings:

BPVDs, i.e., Indian jute fibre drains had enough discharge capacity to accelerate the consolidation of soil. Despite having a smaller discharge capacity than conventional synthetic PVDs (SPVDs) (i.e., $6.8 \times 10^{-6}$ m3/s of BPVDs compared to $10 \times 10^{-6}$ m3/s of SPVDs at 10 kPa confining stress), their ability to dissipate excess pore pressure is almost identical.

Micro-analyses using CT- and optical scanning showed that fibre drains and SPVDs had relatively the same porosity (i.e., 0.8), but the surface area (i.e., fluid-particle contact area) of BPVDs is much larger than SPVDs, which was why BPVDs have a smaller discharge capacity. This study also found that Ballina clay did not clog the fibre drains despite the jute filter having a large AOS of 180 μm of jute filter. There were no fine particles penetrating through the filter under 10 to 50, and 100 and 200 kPa confining stress, so the reduction in discharge volume is insignificant.

Micro-features such as the size, shape, and twisting angle of fibres play a large role in the hydraulic conductivity of fibre drains, such that the larger the fibres, the higher the hydraulic conductivity. The more the fibres are twisted, the smaller the hydraulic conductivity. Although coir fibres account for a smaller volumetric fraction than the jute fibres in the Indian jute drains, their diameter is much larger, i.e., from 91 to 505 μm than jute fibres; obviously this plays a large part in the whole discharge capacity of the drains.

The biodegradation of BPVDs had almost no effect on the consolidation of soil during the 3 year monitoring period at the Ballina project. There was some reduction in the tensile strength of jute drains at the surface depth of 0.5 m beneath the working platform after almost 2 years of installation, but this did not affect the dissipation of excess pore pressure. However, jute drains are not as stiff as conventional SPVDs, and this did seem to result in a larger lateral displacement under the same load. While more examination for this issue is needed, the study indicates that lateral deformation would need appropriate attention when installing fibre drains in the field.

## 5. ACKNOWLEDGEMENT

The authors acknowledge the National Jute Board of India (NJBI) and Australia Research Council for funding this research. Microscopic observations on the samples were carried out at the Australian Institute of Innovative Materials (AIIM), and the Centre for Geomechanics and Railway Engineering, University of Wollongong. This research was also supported by the Australian Government through the Australian Research Council's Linkage Projects funding scheme (project LP140100065) and the Industrial Transformation Training Centre for Advanced Technologies in Rail Track Infrastructure (ITTC), University of Wollongong

## 6. REFERENCES

Arulrajah, A., Abdullah, A., Bo, M.W. and Bouazza, A. 2009. Ground improvement techniques for railway embankments. Ground Improvement, **162**(1): 3-14. doi: https://doi.org/10.1680/grim.2009.162.1.3.

Asha, B.S. and Mandal, J.N. 2012. Absorption and discharge capacity tests on natural prefabricated vertical drains. Geosynthetics International, **19**: 263-271.

ASTM D4716. 2008. Standard test method for constant head hydraulic transmissivity (In-plane flow) of geotextiles and geotextile related products. American Society for Testing and Materials, West Conshohocken, Pa.

Babu, G.L.S. and Vasudevan, A.K. 2007. Evaluation of strength and stiffness response of coir-fibre-reinforced soil. Ground Improvement, **11**(3): 111-116.

Bergado, D.T., Manivannan, R. and Balasubramaniam, A.S. 1996. Proposed criteria for discharge capacity of prefabricated vertical drains. Geotextiles and Geomembranes, **14**(9): 481-505.

Bläsing, M. and Amelung, W. 2018. Plastics in soil: Analytical methods and possible sources. Science of The Total Environment, **612**: 422-435. doi: https://doi.org/10.1016/j.scitotenv.2017.08.086.

Bo, M.W., Arulrajah, A., Horpibulsuk, S., Chinkulkijniwat, A. and Leong, M. 2016. Laboratory measurements of factors affecting discharge capacity of prefabricated vertical drain materials. Soils and Foundations, **56**(1): 129-137. doi: https://doi.org/10.1016/j.sandf.2016.01.010.

Chai, J.C. and Miura, N. 1999. Investigation of factors affecting vertical drain behaviour. Journal of Geotechnical and Geoenvironmental Engineering, **125**(3): 216-226.

Chu, J., Bo, M.W. and Arulrajah, A. 2009. Reclamation of a slurry pond in Singapore. Proceedings of the Institution of Civil Engineers - Geotechnical Engineering, **162**(1): 13-20. doi: doi:10.1680/geng.2009.162.1.13.

Feldkamp, L.A., Davis, L.C. and Kress, J.W. 1984. Practical cone-beam algorithm. Journal of the Optical Society of America A, **1**(6): 612-619.

Gregory, M.R. and Andrady, A.L. 2003. Plastic in the marine environment. *In* Plastics and the Environment. *Edited by* A. L. Andrady. John Wiley & Sons, New Jersey. pp. 379-401.

Indraratna, B., Baral, P., Ameratunga, J. and Kendaragama, B. 2017. Potential biological and chemical clogging of piezometer filters in acid sulphate soil. Australian Geomechanics Journal, **52**(2).

Indraratna, B., Baral, P., Rujikiatkamjorn, C. and Nguyen, T.T. 2019. Soft Ground Improvement—Theoretical, Experimental, Numerical and Field Studies. *In* Frontiers in Geotechnical Engineering. *Edited by* M. Latha G. Springer Singapore, Singapore. pp. 183-216.

Indraratna, B., Baral, P., Rujikiatkamjorn, C. and Perera, D. 2018. Class A and C predictions for Ballina trial embankment with vertical drains using standard test data from industry and large diameter test specimens. Computers and Geotechnics, **93**: 232-246. doi: https://doi.org/10.1016/j.compgeo.2017.06.013.

Indraratna, B., Nguyen, T.T., Carter, J. and Rujikiatkamjorn, C. 2016. Influence of biodegradable natural fibre drains on the radial consolidation of soft soil. Computers and Geotechnics, **78**: 171-180. doi: https://doi.org/10.1016/j.compgeo.2016.05.013.

Jang, Y.S., Kim, Y.W. and Park, J.Y. 2001. Consolidation efficiency of natural and plastic geosynthetic band drains. Geosynthetics International, **8**(4): 283. doi: https://doi.org/10.1680/gein.8.0196.

Kelly, R.B. 2013. Australia's first national facility for soft soils testing. *In* Civil Engineers Australia, June 2013.

Kelly, R.B., Pineda, J.A., Bates, L., Suwal, L.P. and Fitzallen, A. 2017. Site characterisation for the Ballina field testing facility. Géotechnique, **67**(4): 279-300. doi: 10.1680/jgeot.15.P.211.

Kelly, R.B., Sloan, S.W., Pineda, J.A., Kouretzis, G. and Huang, J. 2018. Outcome of the Newcastle symposium for the prediction of embankment behaviour on soft soil. Computers and Geotechnics, **93**: 9-14.

Kim, J.H. and Cho, N. 2008. Pilot scale field test for natural fiber drain. *In Proceedings of the* 4th Asian Regional Conference on Geosynthetics, *Edited by* G. Li, Chen, Y. & Tang, X. Springer-Verlag Berlin Heidelberg, Shanghai, China. pp. 409-414.

Lee, S.L., Karunaratne, G.P. and Aziz, M.A. 2003. Design and performance of Fibredrain in soil improvement projects. Ground Improvement, **7**(4): 149-156. doi: doi:10.1680/grim.2003.7.4.149.

Lee, S.L., Karunaratne, G.P., Ramaswamy, S.D., Aziz, M.A. and Das Gupta, N.C. 1994. Natural geosynthetic drain for soil improvement. Geotextiles and Geomembranes, **13**(6–7): 457-474. doi: https://doi.org/10.1016/0148-9062(95)94764-7.

Lee, S.L., Ramaswamy, S.D., Aziz, M.A., Das Gupta, N.C. and N. C. & Karunaratne, G.P. 1987. Fibredrain for consolidation of soft soils. *In Proceedings of the* Post- Vienna Conference on Geotextiles, Singapore. Vol. **2**, pp. 238-58.

Nguyen, T.T. and Indraratna, B. 2017a. Experimental and numerical investigations into hydraulic behaviour of coir fibre drain. Canadian Geotechnical Journal, **54**(1): 75-87. doi: https://doi.org/10.1139/cgj-2016-0182.

Nguyen, T.T. and Indraratna, B. 2017b. The permeability of natural fibre drains, capturing their micro-features. Proceedings of the Institution of Civil Engineers - Ground Improvement, **170**(3): 123-136. doi: 10.1680/jgrim.16.00032.

Nguyen, T.T. and Indraratna, B. 2019. Micro-CT Scanning to Examine Soil Clogging Behavior of Natural Fiber Drains. Journal of Geotechnical and Geoenvironmental Engineering, **145**(9): 04019037. doi: 10.1061/(ASCE)GT.1943-5606.0002065.

Nguyen, T.T., Indraratna, B. and Carter, J. 2018a. Laboratory investigation into biodegradation of jute drains with implications for field behaviour. ASCE Journal of Geotechnical & Geoenvironmental Engineering, **144**(6): 04018026-1:15. doi: https://doi.org/10.1061/(asce)gt.1943-5606.0001885.

Nguyen, T.T., Indraratna, B. and Rujikiatkamjorn, C. 2018b. Challenges and solutions towards natural prefabricated veritcal drains. Australian Geomechanics Journal, **53**(4): 89-100.

Nguyen, T.T., Indraratna, B. and Rujikiatkamjorn, C. 2018c. A numerical approach to model biodegradable vertical drains. Environmental Geotechnics: 1-32. doi: 10.1680/jenge.18.00015.

Pineda, J.A., Suwal, L.P., Kelly, R.B., Bates, L. and Sloan, S.W. 2016. Characterisation of Ballina clay. Geotechnique, **66**(7): 556-577.

Rujikiatkamjorn, C. and Indraratna, B. 2009. Design procedure for vertical drains considering a linear variation of lateral permeabliity within th smear zone. Canadian Geotechnical Journal, **46**: 270-280. doi: https://doi.org/10.1139/t08-124.

SkyScan 1275. 2016. User manual. Kontich, Belgium.

SkyScan NV. 2011. NRecon user manual.

Som, N., Chattopadhyay, B.C. and Sanyal, T. 2009. A manual on use of jute geotextiles in civil eingieering, 4th Edition. Jute Manufactures Development Council, Kolkata, India.

Taud, H., Martinez-Angeles, R., Parrot, J.F. and Hernandez-Escobedo, L. 2005. Porosity estimation method by X-ray computed tomography. Journal of Petroleum Science and Engineering, **47**(3): 209-217. doi: http://dx.doi.org/10.1016/j.petrol.2005.03.009.

Vinod, P. and Minu, M. 2010. Use of coir geotextiles in unpaved road construction. Geosynthetics International, **17**(4): 220-227.

Wildenschild, D. and Sheppard, A.P. 2013. X-ray imaging and analysis techniques for quantifying pore-scale structure and processes in subsurface porous medium systems. Advances in Water Resources, **51**: 217-246. doi: http://dx.doi.org/10.1016/j.advwatres.2012.07.018.