

# Analytical Modeling of Indian-Made Biodegradable Jute Drains for Soft Soil Stabilization: Progress and Challenges



Kirti Choudhary, Cholachat Rujikiatkamjorn, Buddhima Indraratna and P. K. Choudhury

**Abstract** Installation of vertical drains in soft soil is probably the most popular preloading method of ground improvement today. These drains reduce the consolidation time of the soil by providing alternative pathways to relieve the pore water pressure in the soil quickly thus reducing construction time. Jute drains have been introduced as an environmentally friendly alternative to synthetic drains in recent times. However, owing to higher absorption capacity of jute and their tendency to degrade in soil their consolidation behavior can be vastly different from that of synthetic drains. In this review, the paper provides in detail the properties of jute drains along with significant developments that have been achieved over the years in understanding their consolidation behavior. The clogging and degradation behavior in these drains is investigated in relation to the limitations in analytical modeling. This article aimed to discuss not only the challenges associated with modeling this phenomenon but also suggests approaches by which this problem can be solved.

**Keywords** Analytical modeling · Ground improvement · Jute drains · Preloading · Soft soil stabilization

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## 1 Introduction

Prefabricated vertical drains (PVDs) remain one of the most popular methods of ground improvement for soft clays (Walker et al. 2012; Geng et al. 2012). These drains relieve pore pressure in the ground by providing a horizontal pathway to water by taking advantage of the anisotropy of soil permeability (Indraratna et al. 2014). Although a number of models have been proposed over the years to simulate the consolidation behavior aided by synthetic drains, a number of challenges exist in analytical modeling for natural drains such as those made of Jute. These challenges primarily occur due to higher absorption capacity of jute and their tendency to degrade in soil. Natural fibers such as jute are typically composed of  $\alpha$  cellulose, hemicellulose, and lignin which make the fiber highly hygroscopic. This is in contrast to synthetic drains which are typically made of polyester or polyethylene and are hydrophobic in nature. Cellulose typically breaks down into smaller compounds in the presence of extreme chemical environments. Saha et al. (2012) reported that the degradation of jute fibers is extremely rapid outside the pH range of 4–9. Since soils are typically acidic in nature, these fibers start to degrade after a period of about 6–9 months depending on the acidity of the soil. This phenomenon of degradation tends to reduce the efficiency of natural drains overtime as compared to synthetic drains which are known to last in soil for a period of 12–15 years (Mininger et al. 2011).

Extensive testing to understand the effect of degradation was performed at University of Wollongong (on jute drains provided by National Jute Board of India, NJBI) which includes large scale consolidometer testing of different types of jute drains as well as wick drains at different stages of consolidation and post-processing tests to ascertain the degree of consolidation. To the authors' knowledge, large-scale consolidometer testing in natural prefabricated vertical drains was only carried out once by Asha and Mandal (2015) but that study was largely focused on the effect of compressive stress on the consolidation efficiency of jute drains. Some of the aspects of the study were discussed in this article. A summary of the drains tested in the experimentation program is provided in Fig. 1 and Table 1.



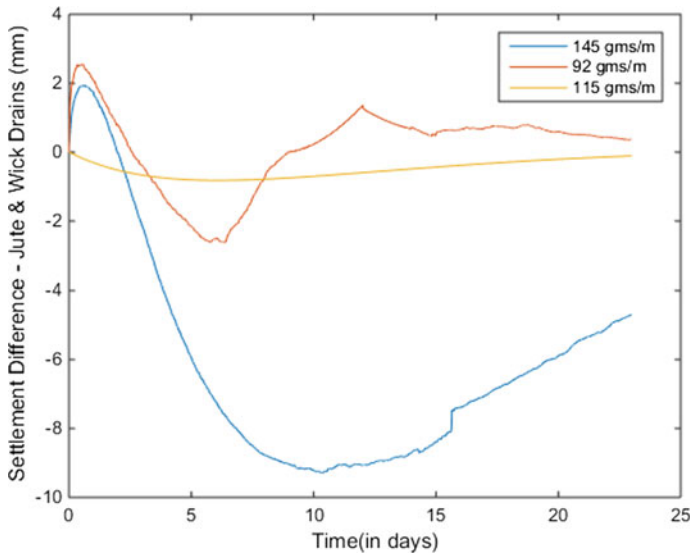
Fig. 1 Jute drains used in the study (drain 1, 2 and 3 from left to right as per Table 1)

**Table 1** List of prefabricated jute drain (PVJDs) tested

Sample No.	Type of PVJD
1	Inter-woven with jute wick 145 g/m
2	Inter-woven with jute wick 92 g/m
3	Inter-woven with coconut coir 115 g/m

Figure 2 shows the differences of settlements for all the cases. It can clearly be seen that Drain 3 performs the best among all the jute drains, and its performance is nearly identical to that of the synthetic drain. Apart from the three types of jute drains mentioned here, a fourth type (PVJD with jute filter coconut coir) was used in the successive consolidation test mentioned later. Based on consolidation test up to 24 months, jute drains perform well considering the fact that degradation happens in these drains.

A review of the challenges associated with modeling consolidation in natural drain sis discussed, and it is suggested the approaches by clogging and degradation can be taken into account. This can significantly improve the modeling accuracy of these drains as most of the existing theoretical or numerical models tend to over-estimate the reduction in pore pressure with time as compared to field data.



**Fig. 2** Differences in settlements of PBJDs that of synthetic wick drain

## 2 Clogging in Vertical Drains

The drain filter surrounding the core primarily serves two functions during the consolidation process: (1) prevent soil particles from entering the core and (2) allow maximum flow of water inside the core so as to allow for maximum possible drainage through the core. For an effective drainage system, a soil filtration system should develop around the drain filter so that any further transport of particles to the core is prevented. The development of such a filtration system is critical to the long-term performance of the drain.

The ability of development of such a filtration system is dependent upon a number of factors such as (McGown 1976):

- Physical and chemical characteristics of the filter jacket
- Soil Characteristics
- Magnitude of external loads or stresses applied on the system
- Hydraulic conditions in and around the filter jacket.

To achieve the required filtration system, a number of criteria were proposed as to what should be the ideal ratio of filter opening to that of the particle size distribution of the soil. One such criteria was given by Carroll (1983) which states that the  $O_{95}$  value of the filter AOS should be less than approximately 2–3 times the  $D_{85}$  of the soil. Here  $O_{95}$  refers to the 95% of the opening size of the geotextile and  $D_{85}$  refers to the soil grain diameter at 85% passing based on particle size analysis.

$$\frac{O_{95}}{D_{85}} \leq 2 - 3 \quad (1)$$

A number of such criteria were summarized and reported by Bergado et al. (1996).

When the effective filter is unable to develop, finer particles in the soil can flow with the water and permeate the filter jacket of the drain to reach the core. This deposition of particles on the filter and in the core leads to the development of an adverse hydraulic potential in the soil near the filter which is detrimental to the flow of water inside the core leading to a reduction in the rate of the consolidation process.

## 3 Theory of Radial Consolidation

### 3.1 Barron's Theory of Consolidation

Barron (1948) gave the solutions for both the equal strain case and the free strain case based on the work of Terzaghi (1925) by considering the flow profiles into and out of an infinitesimally small cylindrical element. The generalized three-dimensional equation of consolidation is given by:

$$\frac{\partial \bar{u}}{\partial t} = C_v \left( \frac{\partial^2 u}{\partial z^2} \right) + C_h \left( \frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} \right) \quad (2)$$

For radial flow only, this equation becomes:

$$\frac{\partial \bar{u}}{\partial t} = C_h \left( \frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} \right) \quad (3)$$

where  $\bar{u}$  is the average excess pore water pressure,  $t$  is time,  $r$  and  $z$  are the cylindrical coordinates,  $C_v$  and  $C_h$  are vertical and horizontal coefficient of consolidation, respectively, and  $u$  is the excess pore water pressure at a given location.

The solution of this equation is obtained using method of separation of variables which results into complicated expressions of  $u$  dependent on Bessel functions of the first and second kind similar to the solutions of the heat transfer equation in cylindrical coordinates. Solutions were also given for the cases where smear and well resistance were included. However, the solutions are cumbersome to compute, and hence for brevity, the mathematical analysis was not discussed here.

### 3.2 Approximate Equal Strain Solution Proposed by Hansbo (1981)

Another equal strain solution was developed by Hansbo (1981) using the equal strain theory, the approximate degree of consolidation ( $U_h$ ) of a soil cylinder consolidated by a vertical drain can be expressed as,

$$U_h = 1 - \exp\left(-\frac{8T_h}{\mu}\right)$$

where the time factor ( $T_h$ ) is given by,

$$T_h = \frac{C_h t}{d_e^2}$$

where  $C_h$  is the horizontal coefficient of consolidation,  $t$  is time and  $d_e$  is the diameter of the influenced zone. The parameter  $\mu$  is given by the following expression:

$$\mu = \ln\left(\frac{n}{s}\right) + \left(\frac{k_h}{k_s}\right) \ln(s) + \pi z(2l - z) \frac{k_h}{q_w} - 0.75 \quad (6)$$

Here  $k_h$  and  $k_s$  are the permeability of the undisturbed zone and smear zone, respectively,  $q_w$  is the discharge capacity of the drain,  $l$  is the height of the vertical

drain,  $n$  is the ratio of the diameter of the influenced zone to that of the drain and  $s$  is the ratio of the diameter of the smear zone to that of the drain.

The second and the third terms in the equation represent the effect of smear and well resistance of the drain, respectively. If these effects are ignored, the value of  $\mu$  simplifies to

$$\mu = \ln(n) - 0.75 \quad (7)$$

## 4 Incorporating Clogging in Modeling of Vertical Drains

Clogging in vertical drains is a time-dependent phenomenon that significantly reduces the efficiency of vertical drains in dissipating excess pore water pressure at the soil–drain interface. In the past, analysis of clogging was restricted to a physical modeling of the particle interface interactions and migration. Considering mass and momentum conservation principles, one can relate properties such as particle size distribution, mass flow rate, and filter capacity to changes in permittivity of the filter medium (Xiao and Reddi 2000). Since it is difficult to model the random arrangement of voids in the filter, assumptions regarding its structure are made and they are usually modeled as a cubic or tetrahedral arrangement. The most fundamental analysis is probably the Kozeny-Carman and the Ergun equations (McCabe et al. 2005; Akgiray and Saatçi 2001)

$$\Delta P = \frac{kV_s\mu(1-\epsilon)^2L}{\phi_s^2D_p^2\epsilon^3} \quad (8)$$

$$\Delta P = \frac{150V_s\mu(1-\epsilon)^2L}{D_p^2\epsilon^3} + \frac{1.75\rho V_s^2(1-\epsilon)L}{D_p\epsilon^3} \quad (9)$$

where  $D_p$  is the diameter of the particle,  $\phi_s$  is the sphericity of the particles in bed,  $\epsilon$  is the porosity of the filter bed,  $V_s$  is the superficial velocity,  $\mu$  is the viscosity of the fluid,  $L$  is the height of the filter bed,  $k$  is a numerical constant, and  $\Delta P$  is the pressure drop across the bed.

Another approach of assessing the permeability of the filter as a function of time is to assume the probabilistic deposition of soil particles in nature. Xiao and Reddi (2000) developed a clogging model based on the assumption that the pores in the filter are long cylinders and asserted that the deposition process of a particle inside these cylinders is a probabilistic process controlled by a lumped parameter. However, the determination of the parameters for different geotextiles is challenging. The lumped parameter for synthetic geotextiles might be different by an order of magnitude in comparison with natural geotextiles.

A similar argument can be given for physical models such as those developed by Locke et al. (2001), these models usually deploy empirically derived equations for

determining viscosity interactions. Such empirical models are usually relevant for a very narrow domain and cannot be generalized for different categories of soils and geotextiles encountered in real engineering problems.

## 5 Degradation Modeling of Jute Vertical Drains

Indraratna et al. (2016) show that there are two parameters affected by degradation of vertical drains; one relates to the discharge capacity,  $q_w$  and others relating to the drain length  $l$  and its equivalent diameter  $d_w$ . While traditional theory applied to radial consolidation (e.g., Hansbo 1981) assumes these parameters to be unchanged or constant during the period of consolidation, in situ degradation makes these parameters time-dependent, hence, adversely affecting the rate of soil consolidation.

The approach elucidated hereinto incorporate degradation of natural jute drains was proposed earlier by Indraratna et al. (2016). The assumption of time invariance of the discharge capacity during consolidation is ignored. Although the reduction in discharge capacity may be influenced by a number of factors, e.g., the characteristics of natural fibers and the soil pH (Kim and Cho 2009), it is further assumed that the degradation process starts immediately upon drain installation. In this context, Indraratna et al. (2016) modeled the rate of degradation of jute drains as an exponential function with time.

In the long term, due to complete degradation, the jute drain simply becomes a tube of concentrated organic matter whose discharge capacity is practically undefined. Therefore,  $q_w$  becomes synonymous with soil permeability. Again, for a simplified solution, constant geometric parameters for the jute drain are assumed over time; thence by geometrically integrating the flow through the whole unit cell, one should be able to obtain the same results as those obtained for a conventional synthetic (prefabricated) vertical drain, PVD. As suggested earlier by Indraratna et al. (2015), the average excess pore pressure of the unit cell  $u$  can be written as:

$$u = \frac{\int_0^l \int_{r_w}^{r_s} u_s(2\pi r) dr dz + \int_0^l \int_{r_s}^{r_e} u_u(2\pi r) dr dz}{V} \quad (10)$$

In Eq. (10),  $u_s$  and  $u_u$  are the excess pore pressures in the disturbed zone and the undisturbed zone, respectively; the geometric quantities  $r_w$ ,  $r_s$  and  $r_e$  are the radii of the vertical drain, the disturbed zone, and influence zone, respectively;  $V$  is the volume of a unit cell having a radius  $r_e$  and a length,  $l$ , to determine its magnitude by  $V = \pi(r_e^2 - r_w^2)l$ .

Having integrated and re-arranged Eq. (10), the time-dependent average excess pore pressure  $u(t)$  is then given by (Indraratna et al. 2016):

$$u(t) = \frac{\gamma_w}{2k_{h,a}} \frac{d_e^2}{4} (\mu_{n,s,a} + \mu_{q,a}) \frac{\partial \varepsilon}{\partial t} \quad (11)$$

In the above,  $\varepsilon$  is the vertical strain of the unit cell;  $\mu_{n,s,a}$  captures the effects of the smear (disturbed) zone and the drain influence zone,  $\mu_{q,a}$  represents the role of reduced discharge capacity, and  $\gamma_w$  is the unit weight of water in the ground (can be brackish in floodplains). As proposed by Indraratna et al. (2016), the magnitudes of  $\mu_{n,s,a}$  and  $\mu_{q,a}$  can be determined algebraically as:

$$\begin{aligned} \mu_{n,s,a} &= \frac{n^2}{n^2 - 1} \left[ \ln\left(\frac{n}{s}\right) + \frac{k_{h,a}}{k_{s,a}} \ln(s) - \frac{3}{4} \right] \\ &\quad + \frac{s^2}{n^2 - 1} \left[ 1 - \frac{s^2}{4n^2} \right] + \frac{k_{h,a}}{k_{s,a}} \left( \frac{1}{n^2 - 1} \right) \left[ \frac{s^4 - 1}{4n^2} - s^2 + 1 \right] \\ \mu_{q,a} &= \frac{2}{3} \pi \frac{k_{h,a}}{q_{w,a}(t)} l^2 \left( 1 - \frac{1}{n^2} \right) \approx \frac{2}{3} \pi \frac{k_{h,a}}{q_{w,a}(t)} l^2 \end{aligned} \quad (12)$$

In the above,  $q_{w,a}(t)$ , is a function that captures the decrease of the drain discharge capacity over time, and its introduction by Indraratna et al. (2016) here makes the solution different to traditional methods.

The well-known relationship between the dissipation of excess pore water pressure (EPP) and the compressibility of soil can also be written as shown below:

$$\frac{d\varepsilon}{dt} = -m_v \frac{du}{dt} \quad (13)$$

where  $m_v$  is the coefficient of volume compressibility for one-dimensional compression. By substituting (13) into (11) and re-arranging, the following expression can be obtained:

$$u + \frac{\gamma_w m_v}{2k_{h,a}} \frac{d_e^2}{4} (\mu_{n,s,a} + \mu_{q,a}) \frac{du}{dt} = 0 \quad (14)$$

As shown by Indraratna et al. (2016), Eq. (14) is an ordinary differential equation with variable time  $t$  and it can be generalized as follows.

$$u + f(t) \frac{du}{dt} = 0 \quad (15)$$

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

$$f(t) = \lambda_a \left( \mu_{n,s,a} + \frac{\lambda_a}{q_{w,a}(t)} \right) \quad (16)$$



where

$$\chi_a = \frac{\gamma_w m_v d_c^2}{8k_{h,a}} = \frac{d_c^2}{8c_{h,a}}$$

$$\lambda_a = \frac{2}{3} \pi k_{h,a} l^2$$

The general solution for Eq. (15) yielding the average EPP  $u_a$  at time  $t$  with a given form of discharge capacity reduction  $q_{w,a}(t)$ , can then be represented by:

$$u_a(t) = u_o \exp\left(-\int_0^t \frac{1}{f(t)} dt\right) \quad (17)$$

Further details of the model derivation and discussion can be found elsewhere in Indraratna et al. (2016).

## 6 Behavior of Jute Drains in Comparison with Synthetic Drain: Field Study

The National Soft Soil Field Testing Facility has been established at Ballina, NSW and is managed by the Australian Research Council Centre of Excellence for Geotechnical Science and Engineering (ARC-CGSE) for conducting various geotechnical trials and soil property investigations (Pineda et al. 2016). A trial embankment: 3 m high, 80 m long, and 15 m wide crest with a side slope set to be 1.5H: 1V was constructed. A working platform, 95 m long, 25 m wide, and 1 m thick, was laid on the existing ground surface to provide drainage. The embankment is divided into 3 sections: two sections are 30 m long and consist of conventional PVD and Jute PVD (biodegradable drain); the third section is 20 m long and consists of conventional PVD with a synthetic drain, but no sand drainage layer. Jute drains were installed in one of the sections to compare its performance with synthetic drains. Vertical drains were installed on a nominally 1.2 m square grid.

As shown in Fig. 3, irrespective of the different properties of jute drains compared to polymeric wick drains, the measured settlement, excess pore water pressure for both drains are very similar to each other. Although the performance of jute drains can be affected by the pyritic (acidic) soil conditions at shallow depths (1–2), the jute drains used in this embankment have more than adequate discharge capacity; hence, the pore pressure dissipation rates between the two types of PVD are expected to be similar, albeit some biodegradation of the jute drains is expected after about 6 months as shown in the recent laboratory experiments at the University of Wollongong, and also verified by examining a jute drain recovered from the Ballina site.

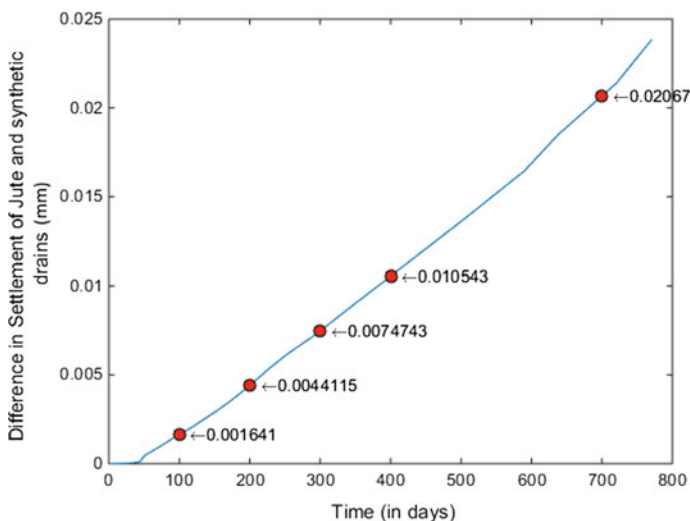


Fig. 3 Comparison of jute and synthetic drain data in terms of settlement

## 7 Conclusion

A number of analytical models proposed in the literature were reviewed and their limitations with respect to modeling natural drains were discussed in detail. The primary issue that limits these numerical models is the lack of provision for modeling clogging and degradation in natural vertical drains and even if such provisions are available their applicability to real-world data is highly limited. Although the applicability of these models to synthetic drains was verified consistently, very few field studies of Jute drains were reported in the literature and hence their verification becomes difficult. It was to bridge this gap that the Ballina field study was carried out incorporating the study of consolidation behavior of both synthetic and jute drains supplied by the National Jute Board of India. Highly acidic soil and groundwater conditions can exacerbate biodegradation in the presence of acidophilic bacteria. Even then, the rate of biodegradation of jute drains may become seriously significant only after about 1.5–2 years upon installation. However, by this time, the consolidation of soft soils would most likely attain a high level of degree of consolidation (i.e. say >95% of primary consolidation). Ballina field trial shows that the degradation of jute drains does not affect the consolidation efficiency even after a year.

**Acknowledgment** This research was supported (partially) by the Australian Government through the Australian Research Council's Linkage Projects funding scheme (project LP140100065). The authors also acknowledge the National Jute Board of India (NJB), Coffey, Douglas Partners, Soilwicks, and Menard Oceania for funding of this research. The Authors would to acknowledge kind permission from Elsevier to reuse some excerpts obtained from Indraratna et al. (2016) in this paper.

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