2017

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## Publication Details

Nguyen, T. T., Indraratna, B., Rujikiatkamjorn, C. & Carter, J. (2017). Finite element modelling of biodegradable jute drains. 15th International Conference of the International Association for Computer Methods and Advances in Geomechanics (15th IACMAG)

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Prefabricated vertical drains made from natural materials such as jute and coir are fast emerging as a practical alternative to synthetic drains because they have excellent engineering properties and they are biodegradable and environment friendly. While previous studies indicate that the biodegradation of drains can sometimes be exacerbated when they are exposed to adverse environmental conditions, thus making the dissipation of excess pore pressure considerably retarded, those which use numerical modelling to incorporate the implications on soil consolidation are limited. This study therefore aims to carry out a numerical investigation based on the Finite Element Method (FEM) to evaluate how biodegradation affects consolidation via a subroutine which can capture the reduction in drain permeability over time and incorporate it into the FEM. Unlike conventional methods which do not consider the drain degradation, the results of this study reveal that the dissipation of excess pore pressure can be retarded when a drain decays rapidly. Subjected to different degradation characteristics such as the degradation with and without an initial intact period, soil consolidates at different rates although the discharge capacity in those cases decreases to the same final value. The numerical solution is also applied to model a laboratory study, and the result shows a certain agreement with experimental data, indicating that FEM with support from the subroutine can capture the influence of drain degradation on soil consolidation well.

**Disciplines**
Engineering | Science and Technology Studies

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# FINITE ELEMENT MODELLING OF BIODEGRADABLE JUTE DRAINS

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**Abstract**

Prefabricated vertical drains made from natural materials such as jute and coir are fast emerging as a practical alternative to synthetic drains because they have excellent engineering properties and they are biodegradable and environment friendly. While previous studies indicate that the biodegradation of drains can sometimes be exacerbated when they are exposed to adverse environmental conditions, thus making the dissipation of excess pore pressure considerably retarded, those which use numerical modelling to incorporate the implications on soil consolidation are limited. This study therefore aims to carry out a numerical investigation based on the Finite Element Method (FEM) to evaluate how biodegradation affects consolidation via a subroutine which can capture the reduction in drain permeability over time and incorporate it into the FEM. Unlike conventional methods which do not consider the drain degradation, the results of this study reveal that the dissipation of excess pore pressure can be retarded when a drain decays rapidly. Subjected to different degradation characteristics such as the degradation with and without an initial intact period, soil consolidates at different rates although the discharge capacity in those cases decreases to the same final value. The numerical solution is also applied to model a laboratory study, and the result shows a certain agreement with experimental data, indicating that FEM with support from the subroutine can capture the influence of drain degradation on soil consolidation well.

**Keywords:** Degradation, Finite Element Method, Discharge Capacity, Numerical Analysis, Consolidation

## 1. INTRODUCTION

The characteristics of biodegradable drains made from natural fibre such as jute, coir and straw, usually possess a large initial hydraulic conductivity and biodegradation occurs over time still giving sufficient time for soil consolidation. In this respect, these natural fibre drains are more environmentally friendly and as effective as synthetic prefabricated vertical drains (SPVDs), hence they have received a lot of attention in recent years [1-4]. One major concern which has been hampering this novel fibre drains from wider applications is the risk of severe degradation under adverse chemical or biological conditions which can seriously retard the dissipation of excess pore pressure (EPP) prematurely during consolidation. Several studies [3-5] indicate that natural prefabricated vertical drains (NPVDs) can decay rapidly in adverse environments such as acid sulphate soil floodplains rich in acidophilic bacteria. Miura et al. [5] report rapid degradation of jute drains buried in Ariake clay at a coastal region of Japan where the drain lost almost 80% of its initial tensile strength after only 128 days. This is why Indraratna et al. [6] tried to clarify how the severe degradation of NPVDs could affect the progress of consolidation in such clay deposits. This study focuses on an analytical approach which requires a particular form of biodegradation such as an exponential reduction of the discharge capacity.

The Finite Element Method (FEM) has been used extensively to predict various types of soil behaviour, particularly soft clay consolidation induced by prefabricated vertical drains (PVDs) [7-9]. In those studies, FEM is commonly used to model vertical drains by assuming they have constant properties, such as the diameter and discharge capacity; unfortunately this can sometimes lead to inaccuracies in predicting soil consolidation where for example, the reduction in discharge capacity is attributed to bending and kinking under large lateral deformation of the soil at shallow depths. In addition to those physical reductions attributed to conventional drains, the discharge capacity of NPVDs can decrease due to biodegradation which tends to damage the porous structure of fibrous media. To enable FEM to be applicable to those cases where the properties of drains vary, conventional FEM analysis must be improved significantly to incorporate biotic and chemical processes that occur naturally in certain ground conditions.

This paper aims to present a numerical approach whereby a subroutine is made to incorporate the reduced permeability of drains into a finite element analysis for soil consolidation. The solution is then used to analyse the influence of drain degradation on soil consolidation considering different cases such as varying the rate and form of decay. A laboratory study where a reduction in discharge capacity during consolidation is captured is further used to validate the numerical method.

## 2. THEORETICAL CONSIDERATIONS

### 2.1 Biodegradation of natural prefabricated vertical drains (NPVD)

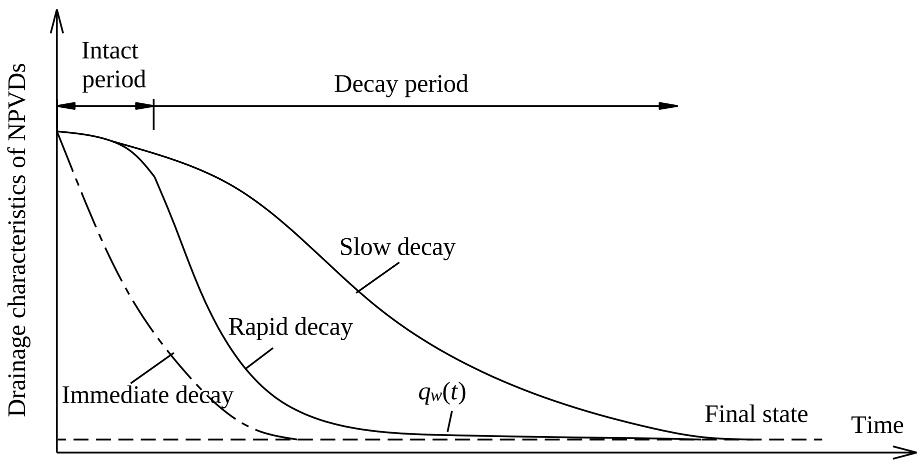



Fig. 1 Various types of degradation in the drainage characteristics of NPVDs

The degradation of drains made from natural fibres is a complicated issue that varies according to environmental and soil conditions such as acidity, temperature, humidity, and the biological activities. A field investigation by Kim and Cho [3] of Kwangyang clay located in the southern coast of Korea in 2009 reveals that the discharge capacity of NPVDs decreases rapidly at the initial stages and then gradually stabilises towards the end. This study also shows how the biodegradation of NPVDs varies over different seasons as the temperature and humidity rise and fall. For simplicity, Indraratna et al. [6] assumes that exponential degradation begins as soon as drains are installed, but this is not always correct because biological studies indicate that natural fibres which usually contain cellulose and lignin might not begin to decompose immediately after NPVDs are installed in saturated soil. This is because, fungi and bacteria take time to colonise and consume the organic materials, particularly in anaerobic soil. An initial delay (intact) period should therefore be considered.

Fig. 1 shows different types of degradation of the drainage characteristics of NPVDs; in this figure, immediate decay and those with an initial intact period followed by a decay time are shown. Theoretically these curves can be described by a particular mathematical time-dependent form $q_w(t)$ or a combination of different forms such as polynomial and exponential functions. However, the more complex the degradation curve, the more challenging is the analytical approach. Because the biodegradation of NPVDs varies under different environmental conditions and the material from which the drains are made, finite element analysis with a more flexible incorporation of drain degradation can provide greater accuracy of the consequential soil behaviour.

Note also that the discharge capacity of a drain is expected to reach a level whereby the natural fibres are completely converted into the organic components of the soil; this means putting a limit value on the discharge capacity while the drain is degrading. Furthermore, geometric parameters such as the length and diameter of a drain well are assumed to be unchanged, while the discharge capacity decreases during consolidation.

## 2.2 Finite element method for a single drain unit

In order to concentrate merely on radial consolidation of soil, a unit cell where consolidation is only induced by a single drain is usually analysed [7, 10, 11]. In this respect, the discharge capacity of the drain is assumed to be unchanged over time. Fig. 2 shows fundamental parameters such as the drain well, and the smear and undisturbed zones of a typical unit cell using the vertical drain. Only a vertical load is applied onto the surface of the cell. How these parameters are determined is discussed in the following parts of this paper.

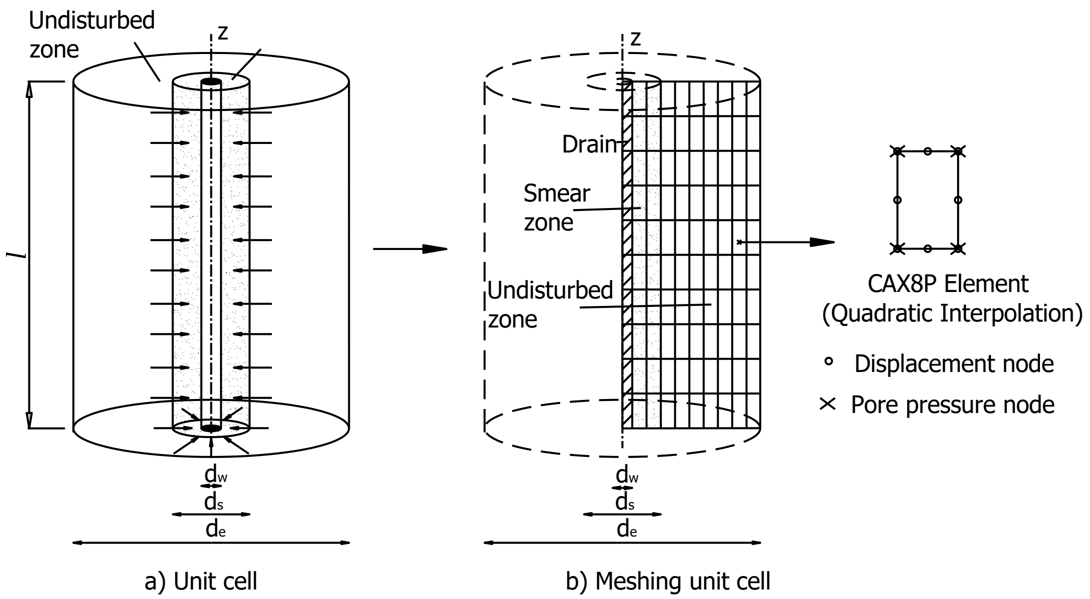



Fig. 2 Apply FEM to a model unit cell of vertical drain

To investigate the influence of drain degradation on the consolidation of soil, FEM is also used in this paper, where the discharge capacity of the drain is assumed to decrease over time. The finite element analysis based on the software code ABAQUS [12] is adopted, and a Fortran subroutine has been created to describe the time-dependent behaviour of the drain. CAX8P elements which indicate axisymmetric analysis with 8 integration nodes (Fig. 2) are used. The discharge capacity of the drain is computed on the basis of the hydraulic conductivity of the drain well, as follows:

$$q_w(t) = k_w(t) \times A_w \tag{1}$$

where $A_w$ and $k_w(t)$ are is the cross-sectional area and the time-dependent hydraulic conductivity of the drain well, respectively. With respect to biology studies [13-15] which show exponential decompositions of organic materials, this paper assumes an exponential degradation in drain discharge capacity, Eq. (1) can therefore be re-written as:

$$q_w(t) = k_{wo}e^{-\omega t} \times A_w \tag{2}$$

where $k_{wo}$ is the initial hydraulic conductivity of the drain and $\omega$ is the decay coefficient representing the rate of reduction in permeability per a unit time. Note that other forms of degradation such as polynomial reductions can also be applied by using the same numerical concept.

Fig. 3 shows how to couple the drain degradation described by the Fortran subroutine with the consolidation of soil modelled by the finite element analysis. At each time step $\Delta t$, the reduction in permeability of the drain is estimated and an updated hydraulic conductivity $k_{wi}$ at time $t_i$ is introduced into the finite element analysis to determine the soil deformation. Because this paper focuses on the dissipation of excess pore pressure, a simple elastic model is used to describe the stress-strain behaviour of the soil. This deformation analysis is coupled with pore fluid diffusion depicted by Biot's consolidation theory adopted in ABAQUS [16]. In the unit cell, a coefficient of volume compressibility $m_v$ = 0.004 $m^2$/kN and Poisson's ratio $\nu$ = 0 indicating no lateral deformation is allowed, are used in the numerical analysis, hence in a practical sense most appropriate for the centerline of an embankment where the lateral deformation is insignificant.


Fig. 3 Numerical scheme of FEM for analysing consolidation considering the degradation of drain

The numerical analysis in this paper assumes that a single prefabricated vertical jute drain (PVJD) is used for a unit cell; the equivalent diameter of the drain well is calculated by $d_w = 2(a+b)/\pi$ where $a$ and $b$ are the thickness and width of the drain. PVJDs commonly include 4 to 5 coir strands wrapped by 1 to 2 layers of jute burlaps. They are normally 8 to 12 mm thick and 80 to 110 mm wide; resulting in an average $d_w$ = 70 mm, which is larger than a normal SPVD, i.e., 50 mm.

The smear zone is determined with reference to the study by Indraratna and Redana [17], whereby the ratio of the diameter of the smear zone to the drain well ($d_s/d_w$) is about 3 to 4. Because PVJDs can be installed the same way as conventional PVDs, the ratio $d_s/d_w$ of 3.4 is used in this numerical analysis. The influence size of the unit cell is assumed to be $d_e$ = 0.6 m and the treatment depth is 20 m. The permeability of undisturbed soil $k_h$ is $5x10^{-9}$ m/s, and the ratio between permeability in the undisturbed and smear zones $k_h/k_s$ of 3.0 is used. The discharge capacity of PVJDs is determined from the laboratory test where $q_w$ = 0.43 $m^3$/day [18]. Impermeable conditions are assigned to the boundary nodes but not at the surface of the drain well. The average excess pore pressure over the unit cell is calculated based on their magnitudes at the nodes.

## 3. RESULTS AND DISCUSSION

### 3.1 Influence of drain degradation on the consolidation of soil

Fig. 4 shows the results obtained from the numerical computation; they indicate how a reduction in the discharge capacity of a drain can affect the consolidation of soil, that is, as the discharge capacity ($q_w$) of a drain decreases the dissipation of excess pore pressure (EPP) is greatly retarded. For example, with a decay coefficient of $\omega$ = 0.02 $day^{-1}$, as $q_w$ decreases to 0.085 $m^3$/day after almost 90 days, the consolidation curve induced by degradable drain apparently begins to deviate from the conventional consolidation approach which considers $\omega$ unchanged over time; after 400 days, while the EPP of the non-degraded drain has almost completely dissipated, the EPP of the degraded curve with $\omega$ = 0.02 $day^{-1}$ is still approximately 11 %.

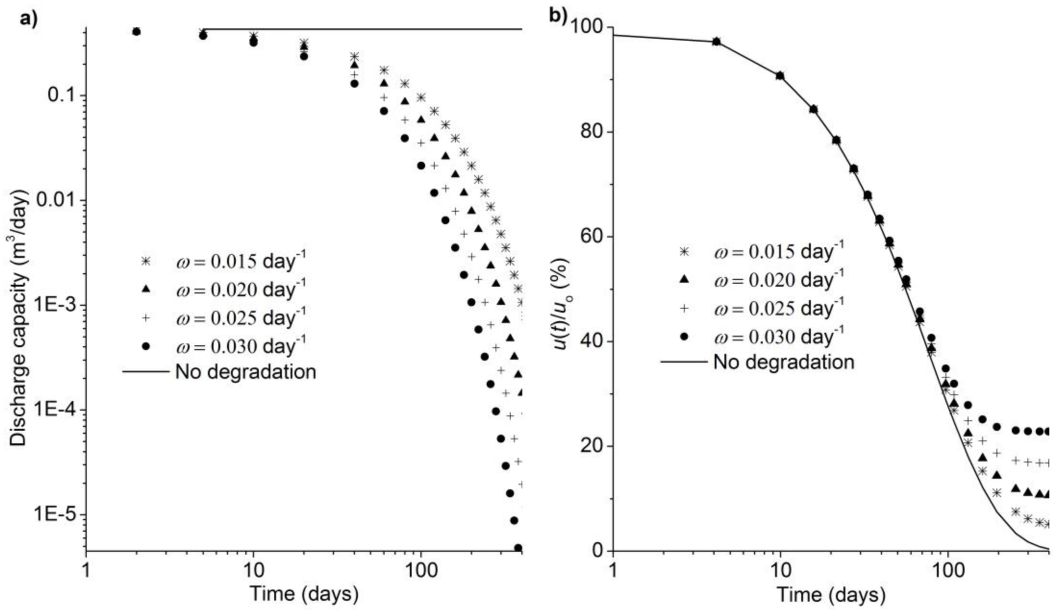



Fig. 4 Influence of drain degradation on soil consolidation: a) different rates of decay, and b) the corresponding consolidation of soil

This numerical investigation also indicates that if the degradation of drains becomes more severe, there is a larger and earlier retardation of consolidation. For $\omega$ = 0.015 $day^{-1}$ the EPP remaining after

400 days is around 5%, but this increases to more than 22% as $\omega$ is doubled in size. Fig. 4 also shows there is a certain small level of discharge capacity in which the discharge of EPP is clearly being blocked. With respect to the properties of soil and the scale of the unit cell used in this study, the critical value of $q_w$ is found to be 0.04 m$^3$/day, and for those periods before this critical value, the difference between the consolidation curves is not significant.

### 3.2 Difference in the form of degradation

There is a vast difference in response of soil consolidation to different forms of degradation in discharge capacity. Fig. 5a shows two types of degradation: one begins as soon as the drain is exposed to adverse media while the other describes an initial delay period where there is very little damage to the drain. In these two situations, $q_w$ decreases to the same level after the same duration, i.e., 2.65x10$^{-6}$ m$^3$/day after 600 days. An intact period of 60 days is assumed in this analysis based on previous biological studies into the decomposition of cellulose materials in anaerobic soil [19, 20]. Note that the case with a delay period has a larger decay coefficient (i.e., $\omega$ = 0.024 day$^{-1}$) to ensure it reaches the same final value as the immediate reduction.

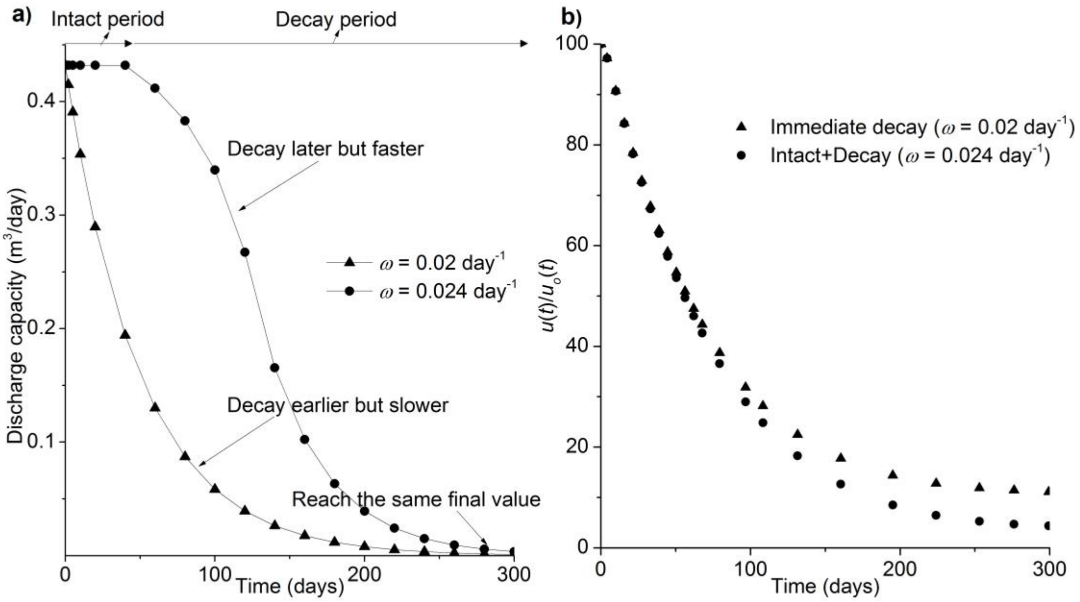
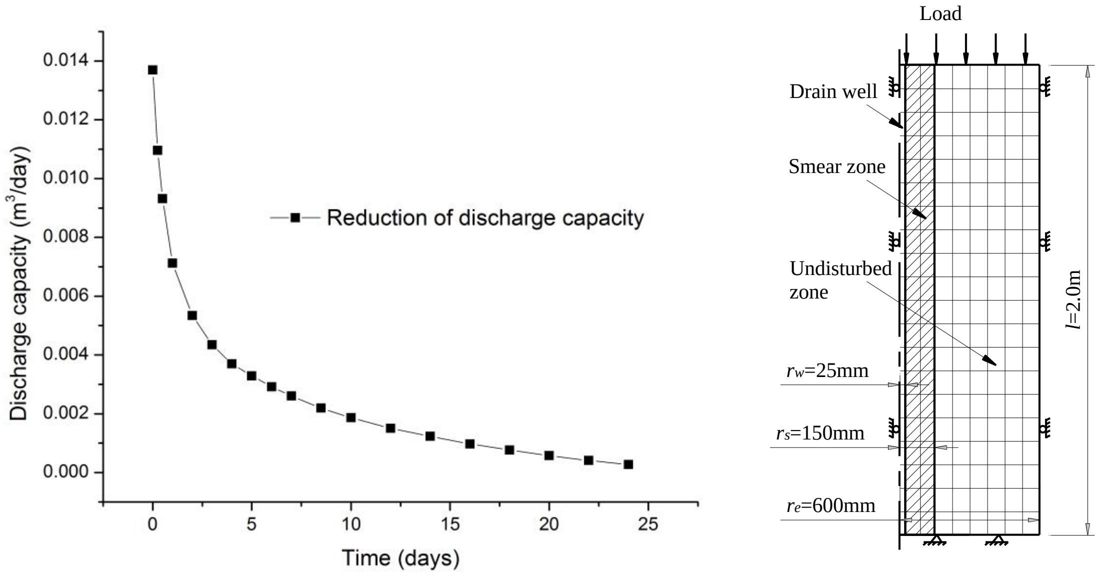



Fig. 5 Influence of difference in degradation of soil consolidation: a) immediate and late degradation of $q_w$; and b) corresponding response of soil consolidation

Fig. 5b shows a deviation between the two corresponding consolidation curves though the decrease in their discharge capacity to the same final discharge capacity. Note that the immediate degradation has a larger excess pore pressure (i.e., 11%) than the one with an initial intact period (i.e., 4% residual) after the same duration of 400 days. This indicates that a drain that degrades when the excess pore pressure is still high has more influence than one for which the degradation occurs later.

Although this numerical investigation only considers two degradation curves, the results shown in Fig. 5 means that it can capture various forms of degradation of the discharge capacity. Unlike the analytical method presented by Indraratna et al. [6] which requires a particular mathematical form of degradation to be incorporated into the governing equation of consolidation, this numerical solution is much more flexible when considering any given discharge capacity reduction trends.

### 3.3 Applying the solution to a laboratory test




a) Reduced discharge capacity b) Finite discretization of unit cell

Fig. 6 FEM modelling degraded vertical drain conducted by Kim et al. [21]

In this section, the numerical approach is used to simulate a laboratory investigation where a reduction in discharge capacity of drain over time has been recorded by Kim et al. [21]. In this study, a large block sample has been extracted from a depth of 12.0 to 14.0 m in a field near the new port at Busan, and then placed into 1.2 m diameter by 2.0 m deep cell for a consolidation test using a vertical drain. A drain with $d_w$ = 5.0 cm has also been installed and a smear effect $d_s/d_w$ = 6 is reported. The initial discharge capacity of the drain installed into the block sample is approximately 5.0 $m^3$/year (0.014 $m^3$/day) which is much smaller than those measured through the discharge capacity test without soil. The reduction in the discharge capacity of the drain has been recorded during the consolidation test, as shown in Fig. 6a. Note that Kim et al. [21] use a wide range of the drain hydraulic conductivity, i.e., $k_w = 5\text{x}10^{-7}$ to $1\text{x}10^{-6}$ m/s.

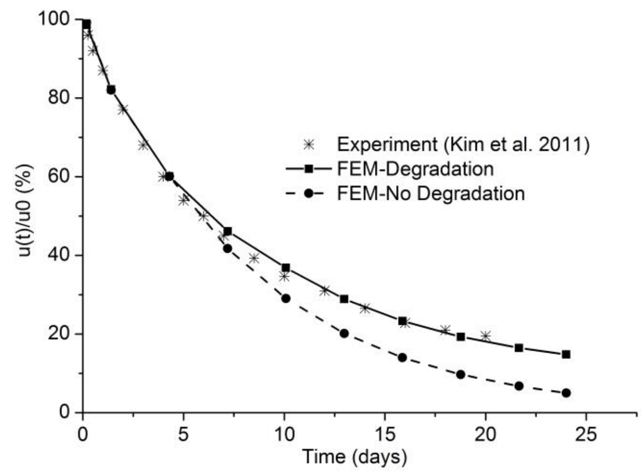



Fig. 7 Validating the numerical method to experimental data

Some of the properties of soil described in the paper by Kim et al. [21] are uncertain because only the parameters of a certain soil layer in the field test are given in detail, and also there is a lack of information regarding the soil sample used in the laboratory consolidation. By back-analysing the consolidation curve given by Kim et al. [21] using the semi-analytical solution described in that work, a consolidation coefficient $c_h$ of 0.155 $m^2$/day can be obtained. The coefficient of permeability $k_h$ = 3.6 x$10^{-10}$ m/s and the ratio $k_h/k_s$ = 2.0 are assumed with respect to the soil properties in the field reported by Kim et al. [21]. A finite element analysis using the subroutine to capture the reduction in discharge capacity has also been carried out (Fig. 6b).

There is a significant deviation between the non-degraded and degraded curves as shown from the finite element analysis (Fig. 7). Note how much the consolidation curves are retarded considerably after 7 days as the discharge capacity decreases to a level less than 0.003 $m^3$/day. As the drain becomes more degraded after 10 days, the dissipation ratio $u(t)/u_0$ induced by degradable drain is almost 10% larger than the drain where the drainage properties do not change. Fig.7 is also a comparison between the dissipation of excess pore pressure (EPP) predicted by the proposed numerical method and the experimental data reported by Kim et al. [21], which indicates an acceptable accuracy of the numerical (FEM) prediction.

## 4. CONCLUSIONS

This paper presented a numerical method where the finite element method (FEM) could incorporate the biodegradation of NPVDs to model soil consolidation. The results indicated that degradation in the discharge capacity of a drain could seriously hamper the dissipation of excess pore pressure, particularly when the discharge capacity decreased to 0.04 $m^3$/day for the soil and natural jute drains used in this study. The different types of degradation such as the immediate and delayed degradation, made a considerable difference to consolidation. Whereas the experimental data reported how drain degradation affected consolidation, the proposed numerical approach showed a good agreement, thus indicating it is a cost-effective way to model the degradation of geomaterials. Finally, unlike the analytical method, this numerical solution is independent of how a drain is degraded, which makes it more capable of capturing various ways of NPVD degradation.

## ACKNOWLEDGEMENTS

The authors acknowledge the National Jute Board of India (NJBI) and Australia Research Council for funding this research. The 1st author's PhD scholarship is sponsored by the Australian Endeavour Scheme.

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