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Evaluation on the performance of field embankment testing biodegradable drains based on spectral method analysis

Évaluation de la performance de remblais avec drains biodégradables par méthode spectrale

Thanh Trung Nguyen, Buddhima Indraratna & Cholachat Rujikiatkamjorn
Faculty of Engineering and Information Technology, University of Technology Sydney, Australia, thanh.nguyen-4@uts.edu.au

Bin-Hua Xu
Geotechnical Engineering Department, Nanjing Hydraulic Research Institute; and College of Civil and Transportation Engineering, Hohai University, Nanjing, China.

ABSTRACT: Biodegradable prefabricated vertical drains (BPVDs) made from natural fibers have received considerable attention in recent years thanks to their benefits to the natural environment, however their application in the field is still limited due to a lack of thorough evaluation on their performance. This was why a field embankment to examine the performance of this novel type of drains was carried out in Ballina (NSW, Australia) from 2013 to 2016. The field data shows that there was certain retardation in the dissipation of excess pore pressure, leading to considerable deviation between the conventional predictions and field data. This current paper thus presents a novel application of spectral method to assess the layered consolidation of soil under the Ballina embankment considering drain degradation. A discharge capacity that varies with time and depth is incorporated into the governing equations of soil consolidation across different layers based on the spectral approach. The results show that a better prediction of soil consolidation induced by BPVDs can be achieved when the proper degradation of drains is considered. The study indicates advantages of the proposed spectral method and the importance of considering drain degradation in practical designs.

RÉSUMÉ: Les drains verticaux préfabriqués biodégradables (BPVD) fabriqués à partir de fibres naturelles ont reçu une attention considérable ces dernières années du fait du bénéfice pour l'environnement. Cependant leur utilisation est encore limitée en raison d'un manque d'évaluation approfondie de leur performance. C'est pourquoi un remblai de terrain a été réalisé à Ballina (NSW, Australie) de 2013 à 2016 pour examiner les performances de ce nouveau type de drains. Les données de terrain montrent un certain retard dans la dissipation de la surpression interstitielle, conduisant à un écart considérable entre les prévisions conventionnelles et les données de terrain. Cet article présente une nouvelle application de la méthode spectrale pour évaluer la consolidation en couches du sol sous le remblai Ballina en tenant compte de la dégradation des drains. Une capacité de décharge qui varie avec le temps et la profondeur est incorporée dans les équations de base de la consolidation du sol à travers différentes couches basées sur l'approche spectrale. Les résultats montrent qu'une meilleure prédiction de la consolidation du sol induite par les BPVD peut être obtenue lorsque la bonne dégradation des drains est considérée. L'étude indique les avantages de la méthode spectrale proposée et l'importance de considérer la dégradation des drains dans en pratique.

KEYWORDS: Biodegradable drains, layered soil consolidation, discharge capacity, spectral method, drain degradation

1 INTRODUCTION

The use of prefabricated vertical drains (PVDs) to improve soft soils has shown significant success over the past years, however conventional PVDs are made from synthetic polymers, resulting in considerable concern with environmental issues. Therefore, biodegradable PVDs have emerged as a favorable alternative thanks to their benefits to the natural environment. Indeed, this type of PVDs stems from natural fibers such as jute and coconut which are biodegradable over time, thus reducing carbon footprint. Moreover, previous laboratory investigations (Asha and Mandal 2012; Jang et al. 2001; Nguyen et al. 2018; Xu et al. 2020) have proved that fiber drains have favorable engineering properties such as good discharge capacity and durability, they can hence accelerate the consolidation progress of soil well. Despite these prominent features, these natural drains have not been used much because there is a lack of thorough evaluation on their performance especially considering field evidence. For example, how the biodegradable properties of natural fibers can affect the consolidation process has not been examined properly. This issue thus requires urgent attention.

A pilot embankment test was therefore carried out in Ballina (Australia) from 2013 to 2016 to examine the performance of biodegradable PVDs. Ballina is a crucial region where the infrastructure is under critical pressure to improve for local transport and economics. In this region, the soft estuarine soil has high to extremely high plasticity with low shear strength and high compressibility characteristics, giving significant

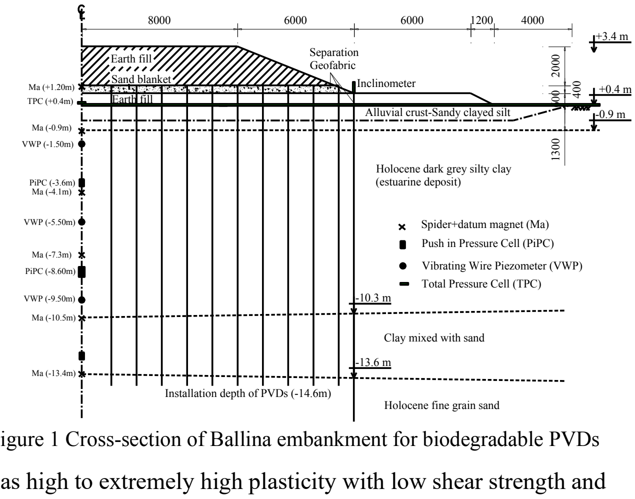

Figure 1 Cross-section of Ballina embankment for biodegradable PVDs

challenges to soft soil improvement and foundation engineering (Kelly 2013). Figure 1 shows a cross-section of the Ballina embankment where the Holocene estuarine soft clay is the major part (i.e., approximately 9 m thick layer) in the Ballina soil profile. Jute drains provided by the National Jute Board of India were installed to a depth of 14 m with a square spacing of 1.2 m. The embankment consisted of an initial 1 m high work platform plus 2 m fill (to a 3 m total height over the original ground surface). A sand blanket was used as a horizontal drainage layer. Further details of this embankment construction can be found in previous investigations (Nguyen et al. 2020).

Previous studies (Indraratna et al. 2016; Nguyen et al. 2018) have indicated that biodegradation of biodegradable PVDs (BPVDs) can affect the dissipation of excess pore water pressure (EPWP) when the degradation rate exceeds a critical level. Most previous investigations are based on analytical and numerical methods where the discharge capacity (q_w) of drains is usually assumed to decrease over time with limited validation to the field condition (Nguyen et al. 2018). Furthermore, previous mathematical approaches cannot be applied well when PVDs are installed in multiple soil layers where soil properties and q_w can change significantly over the depth. Therefore, a more comprehensive and flexible approach has been developed in a recent study (Xu et al. 2021) where spectral method is adopted to predict the consolidation of multi-layered soil with consideration of drain degradation. This current paper aims to further extend this novel method by applying it to predict soil consolidation induced by BPVDs in Ballina embankment.

2 THEORETICAL BACKGROUND AND MODEL DEVELOPMENT

The governing equations of the stratified soil consolidation with a vertical drain, while considering vertical and radial drainage and depth-dependent soil properties, can be given by (Walker and Indraratna 2015) as follows:

$$\frac{m_v}{\overline{m}_v}\frac{\partial \overline{u}}{\partial t} = -dT_h\frac{\eta}{\overline{\eta}}\overline{u} + dT_v\frac{\partial}{\partial \overline{Z}}\left(\frac{k_v}{\overline{k}_v}\frac{\partial \overline{u}}{\partial \overline{Z}}\right) + \frac{m_v}{\overline{m}_v}\frac{\partial \overline{\sigma}}{\partial t} + dT_h\frac{\eta}{\overline{\eta}}u_w \quad (1)$$

$$dT_h\frac{\eta}{\overline{\eta}}u_w - dT_w\frac{\partial}{\partial \overline{Z}}\left(q_w\frac{\partial u_w}{\partial \overline{Z}}\right) = dT_h\frac{\eta}{\overline{\eta}}\overline{u} \quad (2)$$

where $\overline{Z} = \frac{Z}{H}$, $\eta = \frac{k_h}{\mu r_e^2}$, $dT_v = \frac{\overline{k}_v}{\gamma_w \overline{m}_v H^2}$, $dT_h = \frac{2\overline{\eta}}{\gamma_w \overline{m}_v}$, $dT_w = \frac{1}{\gamma_w \overline{m}_v H^2 (n^2-1)\pi r_w^2}$, $\overline{u}$ is the average EPWP at a particular depth, u_w is the prescribed pore pressure in the drain, $\overline{\sigma}$ is the average total stress at a particular depth, *t* is the time, *z* is the depth, *H* is the total depth of the treated soil, γ_w is the unit weight of pore water, m_v is the coefficient of volume compressibility, k_v is the vertical permeability, k_h is the undisturbed horizontal permeability, q_w is the drain discharge capacity, r_w is the radius of the drain, r_e is the radius of influence zone, n is the ratio between r_e and r_w; $\overline{k}_v$, $\overline{m}_v$, and $\overline{\eta}$ are convenient reference values for the relevant parameters; μ is the dimensionless drain parameter, which is related to the smear zone and geometry of the drain.

The pore pressure $\overline{u}(\overline{Z},t)$ and u_w can be expressed as a truncated series of *N* terms by using spectral method as follows:

$$\overline{u}(\overline{Z},t) \approx \sum_{j=1}^{N}\phi_j(\overline{Z})A_j(t) = \boldsymbol{\phi A} \quad (3)$$

$$u_w(\overline{Z},t) \approx \sum_{j=1}^{N}\phi_j(\overline{Z})B_j(t) = \boldsymbol{\phi B} \quad (4)$$

In the matrix $\boldsymbol{\phi}$, $\phi_j(\overline{Z})$ is a set of independent basis functions, and in matrix $\boldsymbol{A}$ and $\boldsymbol{B}$, $A_j(t)$ and $B_j(t)$ are expansion coefficients which can be determined by the operator. Considering the boundary conditions of governing equation, i.e., (*i*) the pervious top and bottom (PTPB) conditions $\overline{u}(0,t) = 0$ and $\overline{u}(H,t) = 0$, and (*ii*) the pervious top and impervious bottom (PTIB) conditions $\overline{u}(0,t) = 0$ and $\partial\overline{u}(H,t)/\partial z = 0$, the suitable basis function can be given by:

$$\phi_j(\overline{Z}) = \sin(M_j\overline{Z}) \quad (5)$$

$$\text{where } M_j = \begin{cases} j\pi & \text{for PTPB} \\ \frac{\pi}{2}(2j-1) & \text{for PTIB} \end{cases} \quad (6)$$

The governing equations can then be given in matrix form by (Xu et al. 2021):

$$\Gamma\frac{\partial A}{\partial t} + \psi A + \zeta A = \theta + \psi B \quad (7)$$

$$\psi B + \chi B = \psi A \quad (8)$$

The elements of the above matrix are given by:

$\Gamma_{ij} = \int_0^1 \frac{m_v}{\overline{m}_v}\phi_i\phi_j d\overline{Z}$; $\psi_{ij} = dT_h\int_0^1 \frac{\eta}{\overline{\eta}}\phi_i\phi_j d\overline{Z}$, $\theta_i = \int_0^1 \phi_i\frac{m_v}{\overline{m}_v}\frac{\partial\overline{\sigma}}{\partial t}\, d\overline{Z}$; $\zeta_{ij} = -dT_v\int_0^1 \frac{\partial}{\partial\overline{Z}}\left(\frac{k_v}{\overline{k}_v}\frac{\partial\phi_j}{\partial\overline{Z}}\right)\phi_i d\overline{Z}$ $\chi_{ij} = -dT_w\int_0^1 \frac{\partial}{\partial\overline{Z}}\left(q_w\frac{\partial\phi_j}{\partial\overline{Z}}\right)\phi_i d\overline{Z}$.

Detailed explicit expressions of the above matrix elements can be found in Xu et al. (2021). Soil parameters such as m_v, k_v, η and k_h are assumed to be linearly distributed in each layer. The total vertical stress is assumed to be the same in the radial direction at the same depth while its value at the upper and lower interface of the certain l^{th} layer is based on Boussinesq's elastic theory.

Solution for the governing equation by spectral method can be given using the initial condition $\boldsymbol{A}(0) = 0$, i.e.,

$$\boldsymbol{A}(t) = e^{-\int_0^t \boldsymbol{\Gamma}^{-1}(\boldsymbol{\psi}+\boldsymbol{\zeta}-\boldsymbol{\psi}(\boldsymbol{\psi}+\boldsymbol{\chi})^{-1}\boldsymbol{\psi})d\tau} \times$$

$$\times\int_0^t e^{\int_0^\tau \boldsymbol{\Gamma}^{-1}(\boldsymbol{\psi}+\boldsymbol{\zeta}-\boldsymbol{\psi}(\boldsymbol{\psi}+\boldsymbol{\chi})^{-1}\boldsymbol{\psi})dt}\boldsymbol{\Gamma}^{-1}\boldsymbol{\theta}d\tau \quad (9)$$

After getting the solution of $\boldsymbol{A}(t)$, the value of EPWP at any depth and time can be obtained by Eq. (3), while the settlement $S(\overline{Z}_l,\overline{Z}_{l+1},t)$ between depths $\overline{Z}_l$ and $\overline{Z}_{l+1}$ can be given by:

$$S(\overline{Z}_l,\overline{Z}_{l+1},t) = H\int_{\overline{Z}_l}^{\overline{Z}_{l+1}} m_v(\overline{Z})\left(\overline{\sigma}(\overline{Z},t) - \overline{u}(\overline{Z},t)\right)d\overline{Z} \quad (10)$$

3 MODEL APPLICATIONS TO BALLINA EMBANKMENT

Considerable attention has been made over the prediction of Ballina embankment in recent years (Amavasai et al. 2018; Chai et al. 2018; Chan et al. 2018; Jostad et al. 2018; Lim et al. 2018; Liu et al. 2018; Müthing et al. 2018), however majority focuses on conventional polymeric PVDs. Although Amavasai et al.(2018) and Le et al.(2018) indicated the reduced discharge capacity is a possible reason causing inaccurate predictions, there is a lack of appropriate studies addressing this degradation of BPVDs. Therefore, this section aims to demonstrate how the spectral method is used to predict Ballina embankment considering drain degradation while assuming that the effects of other factors are negligible.

3.1 Soil and drain properties

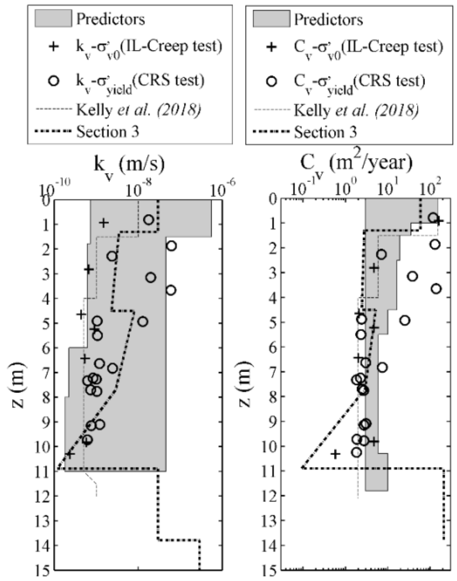

Figure 2 Permeability and coefficient of consolidation with depth.

Figure 2 shows the range of soil permeability and consolidation coefficients of Ballina soil over the depth given in previous studies (Amavasai et al. 2018; Chai et al. 2018; Chan et al. 2018; Jostad et al. 2018; Lim et al. 2018; Liu et al. 2018; Müthing et al. 2018). There is a considerable deviation among different studies as shown in Figure 2. Because some previous studies indicated an overestimated value of the permeability at the lower soft estuarine clay layer ($9 < z < 11$m), the current study has revised those values considering laboratory data (i.e., the dotted lines). The layer properties for modelling Ballina embankment are listed in Table 1. For all clayey soil layers, the relationship between horizontal and vertical permeability is assumed as $\mathrm{k_h}=1.5\mathrm{k_v}$. The history of embankment construction is given in Figure 3, the density of the compacted fill was 20.6 kN/m^3, resulting in a total surcharge load of 61.8 kN/m^2.

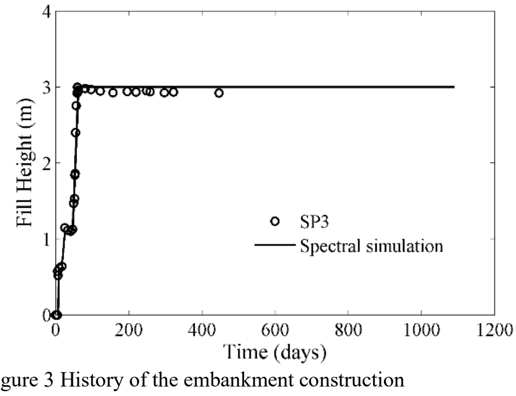

Figure 3 History of the embankment construction

The parameters related to the vertical drain are as follows: (a) the geometrical parameters are d_e = 1.35 m, d_s = 0.32 m, d_w = 0.05 m, $n = r_e/r_w$ = 27.07, $s = r_s/r_w$ = 6.4, and $l = H$ = 15 m, and (b) the permeability ratio is k_h/k_s = 6.

Table 1 Layer properties for modelling of Ballina Embankment

Depth(m)	$m_v/\overline{m}_v$	$k_v/\overline{k}_v$	η/η
0.00	0.53	12.95	12.95
1.30	0.53	12.95	12.95
1.30	1.33	1.50	1.50
4.50	1.00	1.00	1.00
4.50	1.67	3.50	3.50
7.70	1.07	1.25	1.25
10.90	1.33	0.05	0.05
10.90	0.15	12.95	12.95
13.80	0.15	12.95	12.95
13.80	0.03	125.00	125.00
15.00	0.03	125.00	125.00

3.2 Model application

The influence of drain degradation on soil consolidation has been investigated in previous indepdent studies where majority of them agreed that an exponential form can be used to reasonably represent the degradation in discharge capacity of drains over time (Deng et al. 2013; Indraratna et al. 2016; Nguyen and Indraratna 2016; Nguyen and Kim 2019; Xu et al. 2021). Because there is a lack of specific measurement on the reudced q_w in the field, the current study also assumes q_w of BPVDs changes exponentially with time. Furthermore, q_w is assumed to vary linearly over the depth $\overline{Z}$, i.e., $q_w(\overline{Z},t)$. Mathematically, the discharge capacity can be written explicitly as:

$$q_w = q_w(\overline{Z},t) = \begin{cases} q_{w0}(1 - A\overline{Z}l) & t \leq t_c \\ \left(q_{w0}(1 - A\overline{Z}l)\right)e^{-\omega(t-t_c)} & t > t_c \end{cases} \tag{11}$$

where q_{w0} is the initial discharge capacity; A is the coefficient representing the variation of q_w along the depth whereas ω is the degradation rate describing the reduction of q_w over time; and t_c is the starting time of drain degradation. It can be seen that when there is no degradation of drain over time, i.e., $t < t_c$, the value of q_w only decreases over the depth $\overline{Z}$.

In the function of the discharge capacity, the depth and time are two independent variables, therefore, it can be defined as follows:

$$Q_w(\overline{Z}) = q_{w0}(1 - A\overline{Z}l) \tag{12a}$$

$$Q_w(t) = \begin{cases} 1 & t \leq t_c \\ e^{-\omega(t-t_c)} & t > t_c \end{cases} \tag{12b}$$

The function of the discharge capacity can hence be written as:

$$q_w(\overline{Z},t) = Q_w(\overline{Z})Q_w(t). \tag{13}$$

Substituting function $q_w(\overline{Z},t)$ into the elements expression of the matrix χ_{ij}, then the time-dependent matrix $\boldsymbol{\chi}$ is obtained. Further, this enables the integration $\int_0^t \boldsymbol{\Gamma}^{-1}\boldsymbol{\psi}(\boldsymbol{\psi}+\boldsymbol{\chi})^{-1}\boldsymbol{\psi}\boldsymbol{dt}$ which is related to drain degradation, to be solved. Therefore, the influence of drain degradation was incorporated into the consolidation analysis based on the spectral method. Details of this process can be found in Xu et al. (2021).

Previous studies (Asha and Mandal 2012; Chai et al. 2018; Nguyen et al. 2018) conducted discharge capacity tests on Jute BPVDs and found the discharge capacity q_w can vary from 5 to 12 m^3/year. Based on an evaluation through the Class-C analysis by Chai et al. (2018), the value of q_w of Jute BPVDs at 10 m^3/year (0.027 m^3/day) is used in the current model.

Different values of A, ω and t_c are used to model different degrees of drain degradation meanwhile the corresponding results of EPWP and settlement are computed and discussed. Specifically, A = 0, 1/30 and 1/15; ω = 0, 0.012 and 0.02 day^{-1}; and t_c = 63, 100 and 300 days are considered in the following sections.

4 PREDICTION RESULTS AND DISCUSSION

4.1 *Influence of degradation rate ω*

Degradation rate is obviously a key factor directly determining the dissipation of EPWP. Figure 4 compares how different levels of ω changes the dissipation of EPWP based on the proposed model and field data. In this analysis, ω is varied while other degradation factors are unchanged. Without considering degradation (i.e., $\omega = 0$), the dissipation of EPWP occurs much faster, especially at the depth of 6 m. For example, at 400 days, the predicted curve $\omega = 0$ results in about 20.3% difference from the field data. For ω = 0.012 day^{-1}, there is a good agreement between the predicted and measured data across different layers, thus this value can be used to consider biodegradable effects of BPVDs on soil consolidation. Indeed, the difference in the predicted and measure data is less than 4.0% and 3.0% for EPWP and settlement, respectively.

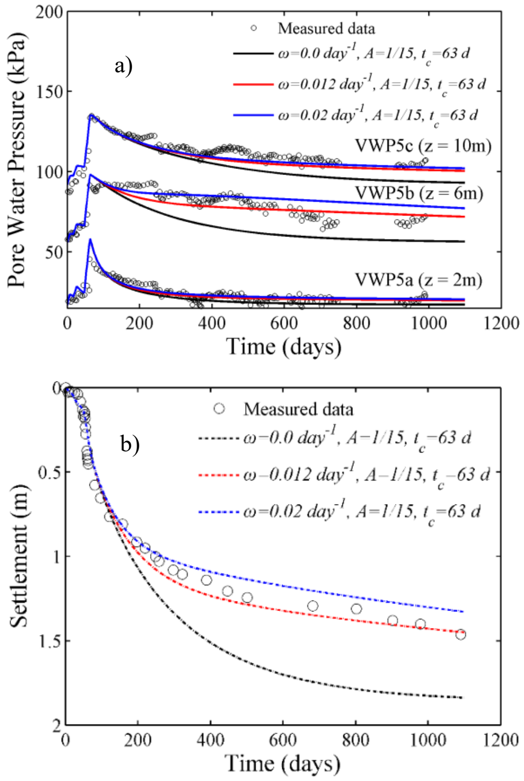

Figure 4 Evaluation of different degradation rate: (a) pore water pressure; (b) surface settlement

4.2 *Influence of depth parameter A*

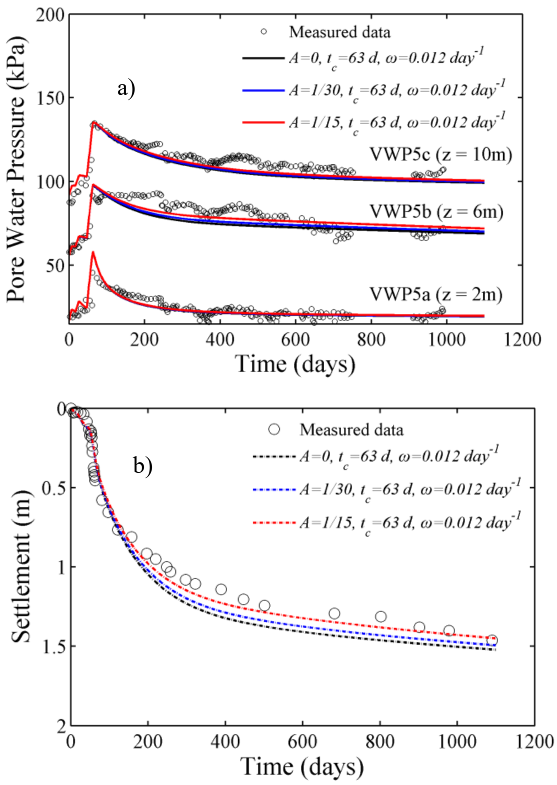

Figure 5 Evaluation of different distribution of q_w: (a) pore water pressure; (b) surface settlement

Figure 5 shows how different values of A can affect the response of EPWP and settlement over time. In this computation, the degradation is assumed to start after 63 days of drain installation (i.e., t_c = 63 d) whereas the degradation rate ω of 0.012 day^{-1} is used. In this analysis, the rate that q_w reduces over the depth, i.e., A increases from zero to 1/30 and 1/15. The larger the value of A, the more the reduction with depth. The results show insignificant influence of A on the dissipation of EPWP and settlement. Nevertheless, A = 1/15 shows a slightly better prediction as there is less deviation between the predicted and measured curves.

4.3 *Influence of starting time t_c*

The starting time t_c is varied to examine how different starts in biodegradation of drains would affect the consolidation progress based on the proposed method. Figure 6 shows the longer the time t_c (i.e., the later the initiation of degradation), the more the deviation between the predicted and measured curves. The study found that t_c varying from 60 to 100 days results in an acceptable prediction. Note that in this analysis, ω and A remain constant.

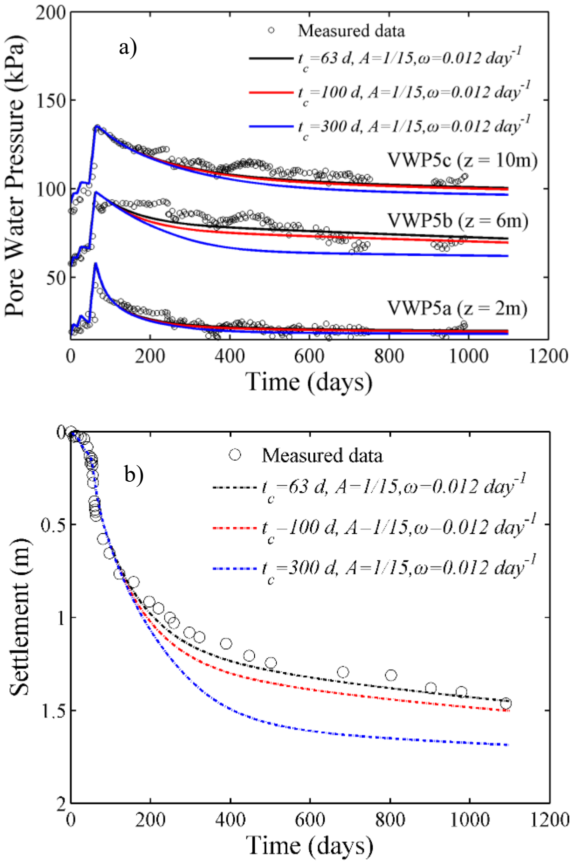

Figure 6 Evaluation of different starting time of drain degradation: (a) pore water pressure; (b) surface settlement

4.4 *Discussion over the role of different degradation parameters*

Considering individual analyses on different degradation factors, i.e., *ω*, *A* and t_c the optimum values which result in the most accurate predictions are selected. Specifically, ω = 0.012 day^{-1}, A = 1/15 and t_c = 63 days are used and the corresponding results are shown in Figure 7. The dissipation of EPWP predicted by the proposed spectral method agrees well the field data, for example, the average difference in the predicted and measured data is less than 3.0% after 400 days. The settlement at different depths given by the prediction also matches well the measured data.

Previous sections also indicate the predominant role of the degradation rate *ω* and starting time t_c in determining how the consolidation progress would develop, whereas the degradation of q_w over the depth shows less influence. Indeed, *ω and* t_c can be determined from laboratory tests where a long term measurement on the discharge capacity of BPVDs installed in soft soil is needed (Nguyen et al. 2018). It is important to note that the current study has assumed the degradation of BPVDs as the major factor causing the retardation in EPWP for simplicity in demonstrating the model application, while ignoring other factors such as such as the change in soil properties and strain rate during soil consolidation. A more comprehensive model which can incorporate different factors is essential to improve the prediction.

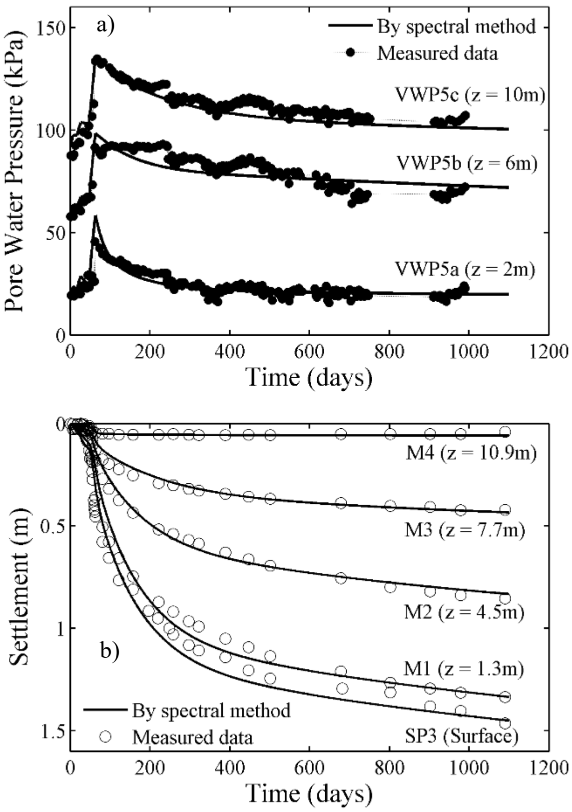

Figure 7 Prediction results with A = 1/15, ω = 0.012 day^{-1} and t_c= 63 d: (a) pore water pressure; (b) layered settlements

5 CONCLUSIONS

This paper represents an application of spectral method to evaluate the potential influence that degradation of biodegradable PVDs (BPVDs) can have on soil consolidation behaviour. The proposed method enables complex characteristics of biodegradation of drains, i.e., the degradation rate, the depth-dependent parameter and the starting time of degradation to be incorporated into the consolidation of multi-layered soil. An application of the method to Ballina embankment where BPVDs were used shows significant success in improving the prediction results by considering degradation of drains. Indeed, the prediction error decreases from 20.3% to less than 3.0% when proper values of degradation factors are used. Despite this certain success, a detailed laboratory investigation to determine accurately the value of degradation factors is needed to enhance the method application in the future projects of BPVDs. The contribution of other factors to the retardation of EPWP also needs consideration.

6 ACKNOWLEDGEMENTS

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