COPYRIGHT NOTICE

FedUni Research Online

<http://researchonline.federation.edu.au>

This is the peer-reviewed version of the following article:

Liu, K., Xue, J., & Yang, M. (2016). Deformation behaviour of geotechnical mat with gas bubbles and time dependent compressible organic matter. *Engineering Geology*, 213, 98-106.

Which has been published in final form at:

<http://dx.doi.org/10.1016/j.enggeo.2016.09.003>

Copyright © 2017 Elsevier B.V. All rights reserved. Published by Elsevier B.V. All rights reserved. This manuscript version is made available under the CC-BY-NC-ND 4.0 license <http://creativecommons.org/licenses/by-nc-nd/4.0/>

Deformation behavior of geotechnical materials with gas bubbles and time dependent compressible organic matter

Kan Liu^{a,b}, Jianfeng Xue^{c,*}, Min Yang^{a,b}

a. Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China;

b. Key Laboratory of Geotechnical & Underground Engineering of Ministry of Education, Tongji University, Shanghai 200092, China;

c. Geotechnical and Hydrogeological Engineering Research Group, Federation University Australia, Churchill, VIC, 3842, Australia.

Corresponding author: Jianfeng Xue

Email: jianfeng.xue@federation.edu.au

[Tel:+61-3-51226448](tel:+61-3-51226448)

Symbols

C	compressibility of materials
C_s	compressibility of solid phase
C_v	consolidation coefficient
e	void ratio
e_g	volume ratio of gas
e_m	volume ratio of organic matter
e_w	volume ratio of water
E_m	initial constrained modulus of organic matter
k	hydraulic conductivity
P_a	atmospheric air pressure
S_g	gas volume content
t	time
t_{50}	time to achieve 50% of total settlement
u	excess pore water pressure
u_a	excess pore air pressure
V	total volume of unit element
V_0	initial total volume
V_g	gas volume
V_{g0}	initial gas volume
V_m	organic matter volume
V_{m0}	initial organic matter volume
V_s	mineral volume
V_w	water volume
w	water content
w_m	organic content
α	initial organic matter volume ratio
ε_m	strain of organic matter
γ_c	unit weight of brown coal
γ_p	unit weight of peat
γ_w	unit weight of water
λ	time factor
σ	total stress
σ'	effective stress
ω_d	degree of decomposition

ABSTRACT: Geotechnical materials may contain organic matters and gas bubbles during the process of their formation. The existence of compressible gas bubbles and organic matters may affect the excess pore water pressure distribution during compression and the deformation behavior of the materials. Immediate settlement and creep have been observed in the early stage of consolidation curves of brown coal and peat samples, which can not be explained with Terzaghi's consolidation theory where soils are considered as fully saturated and soil particles are incompressible. A numerical model has been developed to model the consolidation behavior of brown coal and peat considering the inclusion of gas bubbles and the time dependent compressible organic matters. In the model, the materials are assumed to contain incompressible minerals, compressible organic matters, gas bubbles and water. Consolidation of the materials is considered as a coupling process of water extrusion and volume variation of gas bubbles and organic matters. The model has been validated using the experimental results from one dimensional consolidation curves of brown coal and historical test results of peat. The gas content and the compressibility of organic matters can be obtained using the proposed model. The model can be used to analyze compression behavior of geotechnical materials containing compressible particles and gas bubbles.

Keywords: consolidation model, entrapped gas bubbles, time dependent compressible organic matters, immediate settlement

1: Introduction

Terzaghi's consolidation theory has been widely used to describe the deformation behaviour of saturated porous materials under one dimensional loading. In the theory, the relationship between volume variation with pore pressure changes over time is expressed as:

$$C_v \frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t} \quad (1)$$

where, C_v is the consolidation coefficient; u is the pore water pressure.

For saturated soils with incompressible particles, the volumetric strain ($\Delta V/V$) is affected by the compressibility of the soil (C), the change of total stress ($\Delta\sigma$) and the change of pore water pressure (Δu):

$$\frac{\Delta V}{V} = -C(\Delta\sigma - \Delta u) \quad (2)$$

Skempton (1961) extended Equation (2) to include the compressibility of the solid phase (C_s):

$$\frac{\Delta V}{V} = -C \left[\Delta\sigma - \left(1 - \frac{C_s}{C}\right) \Delta u \right] \quad (3)$$

For clayey material, the C_s/C ratio is very small, therefore Equation (2) can provide an accurate approximation.

There are many conditions when engineering materials are not fully saturated and the voids are filled partly with water and partly with gas. When the soil is partially saturated, gas can be presented in different manners depending on the continuity of the water and gas phases. When gas is continuous, suction plays an important role in

the soil behaviour. Fredlund and Hasan (1979) proposed a consolidation model for unsaturated soils to consider the effect of suction:

$$m_1^w \frac{\partial(\sigma - u_a)}{\partial t} + m_2^w \frac{\partial(u_a - u_w)}{\partial t} = - \frac{k_w}{\gamma_w} \frac{\partial^2 u_w}{\partial y^2} \quad (4)$$

in which m_1^w is the slope of the $(\sigma - u_a)$ vs. $\Delta V/V$ curve when $d(u_a - u_w)$ is zero; m_2^w is the slope of the $(u_a - u_w)$ vs. $\Delta V/V$ curve when $(\sigma - u_a)$ is zero; and σ is the normal stress applied on the soil sample. When the suction is zero, Equation (4) reduces to Terzaghi's consolidation equation.

Faybishenko (1995) proposed the term “quasi-saturated” to describe the concept of a porous material containing trapped gas bubbles. Sparks (1963) and Nageswaran (1983) found that once the degree of saturation is above 0.85, gas would be present in water as isolated bubbles, and the gas bubbles could have different sizes compared to the average grain size (Boudreau, 2012; Mabrouk and Rowe, 2011; Pietruszczak and Pande, 1996; Puzrin et al., 2011; Rebata-Landa and Santamarina, 2012; Wheeler, 1988). Schuurman (1966) studied the compressibility of gassy soils by treating water and gas as a compressible media using Boyle's law. Nageswaran (1983) found that in the presence of gas bubbles, immediate undrained compression was presented in gassy soils, and the amount of immediate settlement increased with gas content.

There are also situations where solid particles are compressible and air bubbles are isolated. Lade and Boer (1997) extended the model by Skempton (1961) to consider the existence of air bubbles in the fluid and the compressibility of particles:

$$\Delta V_{sks} + \Delta V_{sku} = \Delta V_{gs} + \Delta V_{gu} + \Delta V_w + \Delta V_a \quad (5)$$

where ΔV_{sks} and ΔV_{gs} are the volumetric compression of the skeleton and grains due to the change of total confining pressure respectively; ΔV_{sku} and ΔV_{gu} are the volumetric compressions of the skeleton and grains due to the change in pore water pressure respectively; and ΔV_w and ΔV_a are the volumetric compressions of water and air bubbles, respectively. Much research has been conducted thereafter to study the effect of particle and fluid compressibility on the behaviour of geotechnical materials (Borja, 2006; Vlahinic et al., 2011; Schreyer-Bennethum, 2014; Molenkamp, 2014).

Peat and brown coal are both high in organic content and void ratio, low in mineral content, and possibly contain gas (Hayashi and Li, 2004; Dhowian and Edil, 1980; Long and Boylan, 2013). The presence of organic matter has significant effects on engineering properties (Xu et al. 2012; Al-Shamrani, 2005; Cheng et al. 2007). Choo et al. (2015) found that the existence of organic matter may affect the dynamic properties of organoclays. Because of the high organic matter content and the special micro structures, grains of peat and brown coal that contain the organic matter phase are compressible. Some unique consolidation behaviour has been observed in peat and brown coal materials, for example, large deformation, immediate settlement after loading and low permeability (Berry and Poskitt, 1972; Ponziani et al., 2011; Couling et al., 2014; Liu et al., 2014; Lee et al., 2015; Moein, 2015). Some of these phenomena cannot be easily explained with the traditional one-dimensional consolidation theory.

There are limited experimental techniques available to directly measure the gas content and compressibility of materials at the particle scale, and the experiments can be costly if there are any available. Therefore, it is necessary to propose a numerical model that can mathematically estimate the gas content and particle compressibility for engineering practice. To obtain the parameters described in Equation (5), a complex set of experiment is required, and in many cases, these experiments are very difficult for natural materials containing both air bubbles and compressible particles.

The main objective of this paper is to study the deformation behaviour of materials containing gas bubbles and compressible organic matters. A conceptual model of the materials and a mathematical description are proposed to simulate the deformation process. The gas content in the material and the compressibility of the organic matter are estimated by fitting the consolidation curves with the mathematical model. Consolidation curves of two typical organic materials, peat and brown coal, are used to validate the model. The gas content, compressibility of organic matters, and permeability of the materials can be obtained by fitting the experimental results using the model.

2: A Conceptual Model and Assumptions

Peat and brown coal have complex textures and physical composition, and solid phases of the two materials are commonly considered as a mixture of organic matter and minerals. Because of the high content of organic matter, the material grains could

be compressible. Biogas has been found in these materials because of the decomposition of organic matter. Pichan and O’Kelly (2012) discussed that organic matter in peat can be converted into gases including carbon dioxide and methane. The total gas voids content for peats and other organic soils is generally in the range of 5% to 10% (Hobbs, 1986). Even under conventional saturated conditions, small gas bubbles can also be trapped within the voids of material grains. As investigated by Landva and Pheeney (1980), peat can be considered as a three phase material according to the results of a series of scanning electron microscopy tests. As the gas content is low, peat and brown coal can be considered as quasi-saturated. Therefore, a quasi-saturated model with small gas bubbles is proposed to describe the deformation behaviours of the three phase mixture as shown in Figure 1.

3: Mathematical Model for Deformation Behaviours of the Materials

For simplification, the following assumptions are made for the quasi saturated model:

- a) Under initial water content, the materials are considered as quasi saturated consisting of three phases.
- b) The solid phase contains organic and inorganic matter. Organic matter is compressible, and the inorganic mater is assumed to be incompressible.
- c) Water in the materials is continuous, but gas is discontinuous. Gas is disconnected in the form of discrete small bubbles. Water is assumed to be incompressible, and gas bubbles are compressible.

d) The gas bubbles are assumed to be smaller than material grains and are trapped between them. Gas bubbles cannot move with water flow or move from one to another. Gas bubbles are assumed to follow Boyle's Law.

e) The surface tension effect of gas bubbles is neglected. Thus the gas bubble pressure u_g is assumed to be equal to the sum of atmospheric air pressure and water pressure u in the model.

f) Gas dissolution and exsolution are not considered in the model at this stage.

Figure 2 shows the three phase diagram in which the solid phase is composed of organic matter and incompressible minerals. Similar to the definition of the conventional void ratio e , some definitions are introduced as follow:

$$e_m = \frac{V_m}{V_s} \quad e_g = \frac{V_g}{V_s} \quad e_w = \frac{V_w}{V_s} \quad (6)$$

$$\eta = \frac{V_m + V_g + V_w}{V_s} = e_m + e_g + e_w \quad (7)$$

where, e_w , e_g and e_m are volume ratios of water, gas and organic matter, respectively; V_w , V_g , V_m and V_s are the water volume, gas volume, organic matter volume and mineral volume, respectively; and η is the ratio of the changeable volume to the volume of the incompressible solid minerals, which is the sum of e_w , e_g and e_m .

Under the above definitions, the conventional void ratio e can be calculated using:

$$e = \frac{e_g + e_w}{1 + e_m} \quad (8)$$

A parameter α is used to define as the ratio of the initial organic matter volume (V_{m0}) to the initial total volume (V_0), that is:

$$\alpha = \frac{V_{m0}}{V_0} = \frac{e_{m0}}{1 + \eta_0} \quad (9)$$

The gas volume content is defined as:

$$S_g = \frac{V_g}{V_m + V_g + V_w + V_s} = \frac{e_g}{1 + \eta} \quad (10)$$

3.1 Constitutive relations

A unit element is considered with a unit length of 1 for the x and y directions and dz for z direction. For the unit element, the change in volume (ΔV_c) during compression is due to the volume change of gas (ΔV_g), organic matter (ΔV_m) and water (ΔV_w):

$$\Delta V_m + \Delta V_g + \Delta V_w = \Delta V_c \quad (11)$$

During a short time dt :

$$\frac{dV_w}{dt} = \frac{dV_c}{dt} - \frac{dV_m}{dt} - \frac{dV_g}{dt} \quad (12)$$

Assuming water flow in the materials obeys Darcy's law and the hydraulic conductivity k remains constant during the short time period, the change of water volume (dV_w) in the unit element during time dt is:

$$\frac{dV_w}{dt} = \frac{k}{\gamma_w} \frac{\partial^2 u}{\partial z^2} dz \quad (13)$$

where u is the pore water pressure; γ_w is the unit weight of water.

and the change in volume (dV_c) over time dt :

$$\frac{dV_c}{dt} = \frac{1}{1 + \eta} \frac{\partial \eta}{\partial t} dz \quad (14)$$

The effective stress (σ') is defined as:

$$\sigma' = \sigma - u \quad (15)$$

where σ is the total stress. Then:

$$\frac{\partial \eta}{\partial t} = \frac{\partial \eta}{\partial \sigma'} \frac{\partial \sigma'}{\partial t} = \frac{\partial \eta}{\partial \sigma'} \left(\frac{\partial \sigma}{\partial t} - \frac{\partial u}{\partial t} \right) \quad (16)$$

3.2 Compression of entrapped gas bubbles

As mentioned above, the pore air pressure u_g is assumed to be equal to the sum of atmospheric air pressure (P_a) and the pore water pressure u . Thus as a simplification in this stage, the gas phase in the materials is considered as an ideal gas and the deformation obeys Boyle's law, which is:

$$P_a V_{g0} = (P_a + u) V_g \quad (17)$$

where V_{g0} is the initial gas volume. Considering the definitions in Equation (6), the increment of gas volume during a short time dt in the unit element can be calculated as:

$$\frac{dV_g}{dt} = - \frac{e_g}{(1 + \eta)(P_a + u)} \frac{\partial u}{\partial t} dz \quad (18)$$

3.3 Compression of organic matter

Organic matter in the natural deposit of peat and brown coal is different from clay particles. Berry and Vickers (1975) stated that the peat particles may be compressible based on their study on fibrous peat consolidation. However, no detailed studies on the compressibility of organic matter in peat have been conducted. Similar properties have been found in Victorian brown coal (Moein, 2016). The compressibility of the organic matter in peat and brown coal can greatly influence the deformation behaviour of the materials. In Equation (5), Lade and Boer (1997) divided the

compression of particles into two components: a part due to the effective stress and a part due to pore water pressure. However, measurements of the two components are difficult for materials such as coal and peat particles. To simplify this problem, a stress-strain-time model is proposed here to describe the compressibility of organic matter in peat and brown coal due to the total stress:

$$\varepsilon_m = \left(\frac{1}{E_m}\sigma\right)\left(\frac{t}{t_1}\right)^\lambda \quad (19)$$

where, ε_m is the strain of organic matter; σ is the applied vertical total stress; t_1 is the unit time; E_m is the initial constrained modulus of the organic matter; and λ is the time factor.

The volume of organic matter can be calculated using:

$$V_m = V_{m0}(1 - \varepsilon_m) \quad (20)$$

Substitute Equations (19) and (9) into Equation (20), we can get:

$$V_m = \alpha V_0 \left[1 - \left(\frac{1}{E_m}\sigma\right)\left(\frac{t}{t_1}\right)^\lambda \right] \quad (21)$$

The increment of organic matter volume during a short time dt in the element can be calculated using:

$$\frac{dV_m}{dt} = -\alpha \frac{1}{E_m} \left(\frac{\partial \sigma}{\partial t} t^\lambda + \lambda \sigma t^{\lambda-1} \right) dz \quad (22)$$

In this equation, the volume change in organic matter is considered as the change of the applied total stress, which is a simplification of the model considered in Equation (3), where the volume change in particles is considered separately due to the change of effective stress and pore water pressure.

Substituting Equations (14) (18) (22) into (12), then (12) into (13), the consolidation model of soils with compressible organic matter and gas bubbles can be described as:

$$\frac{k}{\gamma_w} \frac{\partial^2 u}{\partial z^2} = \frac{1}{(1+e)(1+e_m)} \frac{\partial \eta}{\partial \sigma} \left(\frac{\partial \sigma}{\partial t} - \frac{\partial u}{\partial t} \right) + \alpha \frac{1}{E_m} \left(\frac{\partial \sigma}{\partial t} t^\lambda + \lambda \sigma t^{\lambda-1} \right) + \frac{S_g (1+\eta)}{(1+e)(1+e_m)(P_a + u)} \frac{\partial u}{\partial t} \quad (23)$$

The one-dimensional finite difference form of Equation (23) is employed to solve this equation in Excel. By fitting the numerical and experimental consolidation curve, the compressibility of organic matter, gas content, permeability and time factor (λ) can be determined. The model is validated using a set of historical consolidation data for peat and experimental results of Australian brown coal samples.

4: Validation of the model with Victorian brown coal

4.1 Material properties and consolidation tests

To test the performance of the model, consolidation curves of brown coal samples are modelled. Undisturbed Victorian brown coal samples were taken from Yallourn Open Cut Latrobe valley, Victoria, Australia at a depth of 45 m below the ground surface. Brown coal in Victoria is a low rank coal and is mainly used for power generation. The material is different from both conventional soils and rocks. It's softer than rock and harder than soils with undrained shear strength in the range of 300 kPa to 500 kPa or higher (Durie, 1991). Thus Victorian brown coal is usually considered as an Intermediate Geotechnical Material. It is high in organic content (>90%), water content (up to 200%) and void ratio (2 or higher), and low in specific gravity (1.5) and

hydraulic conductivity (10^{-10} m/s) (Durie, 1991; Liu et al., 2014). Under original saturated situation, brown coal is black and can change into brown color when dried. The overconsolidation ratio of brown coal with in the mining depth is normally greater than 2, and can be up to 10 at shallower depth (Durie, 1991). The material can be considered as porous material upon drying (Durie, 1991). Figure 3 shows some pictures of undisturbed brown coal samples.

One dimensional consolidation tests were carried out using a conventional oedometer. The brown coal samples were 6.18 cm in diameter with a thickness of 2 cm. Only one way drainage was allowed in the tests to increase the drainage path, and settlement was measured at every second during the first minute of the test, so that the early stage of the settlement curve can be better observed. Three brown coal samples were tested. For sample 1, the applied total vertical stresses were 85-170-340-680-1360 kPa. For samples 2 and 3, the applied total vertical stresses were 85-184-382-776-1565 kPa. The properties of the brown coal samples are shown in Table 1. In the table, the organic content w_m is the ratio of the mass of organic matter to the mass of total solid matter; water content w is the ratio of the mass of water to the mass of total solid phase.

The settlements with time under different stresses were measured for each sample. The settlement curves of sample 1 are presented in Figure 4. In the figure we can see that there is an instantaneous settlement at the early stage of the consolidation process. The deformation pattern of the consolidation curve differs from a typical consolidation curve observed in other soils such as saturated clay, which starts with a

gentle curve and then steepens. The immediate settlement contributes to more than 50% of the total settlement occurring in the first 0.1 minutes. The settlement curve becomes almost linear with time in the log time scale after 0.1 minutes. From this figure we can see that it is not possible to adopt the graphic method, which is normally referred as Casagrande method, to determine t_{50} , i.e. time to achieve 50% of total settlement. Therefore, the graphic method cannot be used to derive other parameters such as permeability, 100% consolidation and the coefficient of consolidation of the material either.

4.2 Modelling

The experimental results were modelled with the proposed method using the parameters listed in Table 2. The modelled time and settlement curves are shown in Figures 5 to 7 with the comparison to the experimental results and predictions from Terzaghi's equation. To compare the results, time is plotted in the normal scale instead of log scale. The results show that immediate settlement occurred in all the samples. Under the same loading level, the samples showed slightly different amount of immediate settlements. It can be seen that the immediate settlement observed in the first few seconds of the tests can be well captured with the proposed model. The constrained modulus of organic matter in brown coal is in the range of 25 to 35 MPa, which is less than 2% of the bulk modulus of water (2.2 GPa) and higher than that of air (0.1MPa at constant temperature). The permeability of the samples obtained from the model is in the range of 10^{-11} m/s. This value is less than the findings from falling head tests (10^{-10} m/s) by Liu et al. (2014). This because the permeability tests were

carried out under low stress levels (lower than 50 kPa), but the stress for consolidation tests is higher.

A small value (in the range of 0.04) is obtained for the time factor (λ). This suggests that the creep effect of organic matter is not significant in the tested brown coal samples, as reflected in the gentle slope in the consolidation curve at the late stage of the consolidation process, i.e. after 4 hours. The gentle slope part in the consolidation curve can be better described using the proposed model than using Terzaghi's equation, which gives a relatively flat consolidation curve after 4 hours. The modelled gas content in the samples is relatively low, i.e. less than 1%.

5: Application of the model to historical data

5.1 Case 1 Peat from North eastern China

Lv et al. (2011) carried out a set of one dimensional consolidation tests on five peat samples with different organic contents. The peat samples were 7.98 cm in diameter and 2 cm in height. A vertical load of 50 kPa was applied on each sample. Some properties of the five samples reported by Lv et al. (2011) are shown in Table 3. They found that with the increase in organic content the samples presented different consolidation behaviours. With the increase in organic content, the coefficient of volume compressibility increased and the coefficient of consolidation decreased. The authors observed that there was almost a liner relationship between time and settlement in the first few minutes and that part of the settlement contributed to a large percentage of the total settlement.

The test results are modelled with the proposed consolidation model and compared with the results from Terzaghi's equation where the gas content is considered to be zero and solid matter is incompressible. The parameters used in the proposed model are listed in Table 4. In the table, e_g and e_m were calculated from the geotechnical indexes listed in Table 3. E_m , λ , k and S_g are the parameters to be determined by fitting the experimental results to the modelled consolidation curves. The results are compared in Figure 8 with the consolidation curves from equation (1). The figures showed that, without considering the compressibility of the organic matter and gas bubbles, the consolidation curves predicted using Terzaghi's equation are very smooth in the first few minutes. However, the sudden settlement observed in the test results cannot be fully captured, while the proposed model is able to describe the test results quite well.

Table 4 shows that the gas content and the constrained modulus of the organic matter in the samples obtained from the model are different in the five samples. Gas content is within the range of 2% to 5%, and the value increases with the void ratio as shown in Table 4. In general, the constrained modulus decreases and the gas content increases with the degree of decomposition as shown in Tables 3 and 4. The constrained modulus of the organic matter ranges from 0.8 to 5 MPa. The values are slightly higher than the initial constrained modulus E_0 of Szczecin peat found by Meyer (1997). This may be because the initial constrained modulus considers the compressibility of both peat and gas in the peat samples.

5.2 Case 2: Middleton Peat from Wisconsin, USA

Mesri et al. (1997) carried out a series of consolidation tests on peat samples taken from Middleton, Wisconsin, USA. The peat properties are shown in Table 5. In all the test results, immediate settlement was observed in the samples. In their study, the authors focused on the secondary consolidation behaviour of the material as they found that secondary consolidation started in the consolidation tests after 15 minutes. The initial immediate settlement was not explained in the original publication.

Five of the test results from Mesri et al. (1997) were analysed using the proposed model to study the effect of compressibility of solid particles and gas content on the consolidation behaviour of the material. In each test, the samples were loaded to different loading levels. The parameters used in the proposed model are listed in Table 6. The modelled settlement curves of the peat samples are compared with the results from the experiment and Terzaghi's equation in Figure 9.

The constrained modulus of the organic matter obtained for the peat samples is relatively consistent compared with that of the peat samples from North eastern China used in case 1. This may be because the peat samples used in Mesri et al. (1997) were from a 2.5 m by 2.5 m test pit, which suggests that the variation of the properties in the peat samples could be less compared to the samples used by Lv et al. (2011) where the peat samples were from a relatively larger area. Apart from that, the moduli of the organic matter from the two cases are in a similar range based on the modelled

results.

The constrained modulus of organic matter obtained from the model is much lower than the values of coal. That is because peat samples are normally consolidated but brown coal in the Latrobe Valley is highly over consolidated with an overconsolidation ratio in the range of 10 or above at the depth where the samples had been taken (Moein et al. 2015). Therefore, the fibrous structure in peat is much more compressible compared to coal particles.

The time factor obtained from the model for coal is only approximately 15% of that of peat as shown in Tables 2, 4 and 6. This suggests that the creep effect of the solid particles is less in coal. This may be because the hollow structure in the fibres in peat samples is well maintained as shown in Mesri et al. (1997), and the deformation of the hollow fibres may contribute to the creep of the organic particles which results in higher λ values. The gas content in the brown coal samples is only in the range of 0.6, which is much less than that in the peat samples.

6: Parametric analyses

In the above sections, a numerical model was established to study the consolidation behaviour of geotechnical materials containing organic matter and gas bubbles. In the model, the constrained modulus of organic matter E_m , gas content S_g and time factor λ considering the creep of organic particles were used. To study the effect of each parameter on the consolidation behaviour of the materials, sensitivity analyses were

carried out in this section. Two consolidation curves from peat and coal, i.e., peat sample 3 in case study 1 and brown coal sample 1 under vertical stress of 340 kPa, were used in the following studies.

In the analysis, only one of the three parameters of E_m , S_g and λ is considered in the consolidation model. For example, when considering the elastic compression of organic matter, S_g and λ are set as zero to neglect the existence of gas bubbles and the creep of organic matter. The results are shown in Figure 10 (a) and (b). Figures 5 to 9 show that the consolidation curves are almost linear after a few hours, therefore in Figure 10, only the results of the first 4 hours are shown to better reveal the transition of consolidation curves at the early stages. The results show that the initial immediate settlement is mainly due to the existence of gas bubbles and the compressibility of organic matter. The time factor λ has little effect on the consolidation curve in the early stage of the consolidation process. The contribution of each component to the immediate settlement is affected by the percentage of organic content and gas content, as well as the compressibility of the organic matter. For the case of peat, the gas content contributes more to the initial settlement due to the relatively high gas content. However, in brown coal, the compression of gas and coal particles contributes almost the same to the initial settlement. This suggests that the combination of gas content and particle compressibility affect the early stages of the materials' consolidation behaviour, while the time factor affects the creep of the samples in the late stage of the consolidation curves.

To reveal the contribution of each phase to the total settlement, Figure 11 shows the

deformations caused by each phase during the consolidation process. The consolidation curve of brown coal sample 1 under a pressure of 340 kPa is taken as an example. In Figure 11, Line 1 to Line 3 represent deformations caused by the compression of organic matter and gas bubbles, and water drainage respectively. The modelled total deformation is the sum of these 3 lines. It can be seen from Line 1 and Line 2 that immediate settlement occurs due to the compressibility of organic matter and gas bubbles. The results show that gas volume recovers as excess pore water pressure dissipates, unlike the deformation occurring in the organic matter.

7: Conclusions

With high content of organic matter in the natural deposits, peat and brown coal have special natural characteristics and engineering properties. Biogas such as methane could be generated from the natural deposits and may be trapped as gas bubbles in the materials during migration. Peat and brown coal containing fossilized organic materials have special composition and structure and the organic matter in the materials could be compressible. Therefore, similar consolidation behaviours have been observed in peat and brown coal, such as immediate settlement in one dimensional consolidation tests and creep of particles. Due to the variation of gas content and compressibility of the organic matter in the materials, it is hard to physically determine the gas content and the compressibility of the parameters.

A quasi-saturated conceptual model was proposed to consider the presence of organic matter and entrapped gas bubbles in the two materials. In the model, the

material was assumed to contain gas bubbles, water, compressible organic matter and incompressible minerals. The consolidation of peat and coal was considered as a coupling process of the volume change of gas bubbles, compression of organic matter and the exclusion of water. The model also considered the creep of organic matter during consolidation using a time factor. Some historical data on peat and experimental results on Australian brown coal were used to validate the model by fitting the experimental results with the modelled consolidation curves.

The modelled and experimental results showed that the proposed model could well capture the unique consolidation behaviour of granular materials containing organic matter. The gas content, constrained modulus of organic matter, permeability and the time factor considering the creep of organic matter can be obtained using the model. Based on the experimental and numerical modelling results, it can be concluded that:

1: The immediate settlement observed in Australian brown coal and the peat samples was due to the existence of gas bubbles and the compressibility of the organic matter. The proposed model can be used to model this process. In the model, the compression of organic matter was due to the change in total stress. The gas content and constrained modulus of the organic matter can be obtained by fitting the experimental results and results from the numerical model.

2: The early start of creep effect observed in the materials during consolidation tests was due to the creep of organic matter in the materials and can be modelled with a stress-strain-time model using a time factor. The creep in peat was much greater than that in brown coal, which was reflected in a larger value of the time factor for the peat

samples.

3: Based on the modelled result of the samples, the initial constrained modulus of brown coal organic particles was in the range of 25 to 35 MPa, while the value for the peat particles was in the range of 0.8 to 5 MPa. The large range of peat organic matter compressibility was probably due to the degree of decomposition.

The proposed model proved to be effective in analysing the consolidation behaviours of brown coal and peat, which contained both gas bubbles and compressible organic matter. Though some simplifications were made in the established model, it has the potential to be used for modelling the compression behaviours of similar engineering materials and can be used to indirectly estimate the gas content and compressibility of solid particles. More advanced tests should be carried out on such materials to validate the model and to determine the parameters used in the model, such as undrained compression and image processing techniques. Such work is currently underway by the authors.

Funding

This work is supported by the National Natural Science Foundation of China under Grant No. 41572258.

Acknowledgements

Part of the work in this paper was completed at Monash University, Australia, where the first author worked as a visiting student. The authors acknowledge the support

received from the organization and Prof. Rae Mackay in developing the model used in the paper.

References

- Al-Shamrani, M.A., 2005. Applying the hyperbolic method and C_a/C_c concept for settlement prediction of complex organic-rich soil formations. *Eng. Geol.* 77, 17-34. DOI: 10.1016/j.enggeo.2004.07.004.
- Berry, P.L., Poskitt, T.J., 1972. The consolidation of peat. *Géotechnique*. 22(1), 27-52.
- Berry, P.L., Vickers, B., 1975. Consolidation of fibrous peat. *J. Geotech. Eng. ASCE*. 101(8), 741-753.
- Borja, R.I., 2006. On the mechanical energy and effective stress in saturated and unsaturated porous continua. *Int. J. Solids Struct.* 43(6), 1764-1786. DOI: 10.1016/j.ijsolstr.2005.04.045.
- Boudreau, B.P., 2012. The physics of bubbles in surficial, soft, cohesive sediments. *Mar. Petrol. Geol.* 38(1), 1-18. DOI: 10.1016/j.marpetgeo.2012.07.002.
- Cheng, X.H., Ngan-Tillard, D.J.M., Den Haan, E.J., 2007. The causes of the high friction angle of Dutch organic soils. *Eng. Geol.* 93, 31-44. DOI: 10.1016/j.enggeo.2007.03.009.
- Choo, H., Bate, B., Burns, S.E., 2015. Effects of organic matter on stiffness of overconsolidated state and anisotropy of engineered organoclays at small strain. *Eng. Geol.* 184, 19-28. DOI: 10.1016/j.enggeo.2014.10.022.
- Couling, C., Tolooiyan, A., Mackay, R., Xue, J., 2014. Measurement of pore water pressure properties of unsaturated brown coal using triaxial test. *Unsaturated Soils:*

- Research and Applications-Proceedings of the 6th International Conference on Unsaturated Soils, Sydney, pp. 1531-1535.
- Dhowian, A.W., Edil, T.B., 1980. Consolidation behavior of peats. *Geotech. Test. J.* 3(3), 105-114.
- Durie R.A., 1991. *The Science of Victorian Brown Coal: Structure, Properties and Consequences for Utilization*, Butterworth Heinemann.
- Faybishenko, B.A., 1995. Hydraulic Behavior of Quasi - Saturated Soils in the Presence of Entrapped Air: Laboratory Experiments. *Water Resour. Res.* 31(10), 2421-2435. DOI: 10.1029/95WR01654.
- Fredlund, D.G., Hasan, J.U., 1979. One-dimensional consolidation theory: unsaturated soils. *Can. Geotech. J.* 16(3), 521-531. DOI: 10.1139/t79-058.
- Hayashi, J.I., Li, C.Z., 2004. *Advances in the Science of Victorian Brown Coal: Structure and Properties of Victorian Brown Coal*. Elsevier, Melbourne.
- Hobbs, N.B., 1986. Mire morphology and the properties and behavior of some British and foreign peats: *Q. J. Eng. Geol. Hydroge.* 19(1), 7-80. DOI: 10.1144/GSL.QJEG.1986.019.01.02.
- Lade, P.V., De Boer, R., 1997. The concept of effective stress for soil, concrete and rock. *Géotechnique*. 47(1), 61-78. DOI: 10.1680/geot.1997.47.1.61.
- Landva, A.O., Pheeney, P.E., 1980. Peat fabric and structure. *Can. Geotech. J.* 17(3), 416-435. DOI: 10.1139/t80-048.
- Lee, J.S., Seo, S.Y., Lee, C., 2015. Geotechnical and geophysical characteristics of muskeg samples from Alberta, Canada. *Eng. Geol.* 195, 135-141. DOI: 10.1016/j.enggeo.2015.04.030.
- Liu, K., Mackay, R., Xue, J., Tolooiyan, A., 2014. Experimental study of brown coal hydraulic behavior at low confining stress. *Unsaturated Soils: Research and*

- Applications-Proceedings of the 6th International Conference on Unsaturated Soils, Sydney, pp. 1125-1130.
- Long, M., Boylan, N., 2013. Predictions of settlement in peat soils. *Q. J. Eng. Geol. Hydroge.* 46(3), 303-322. DOI: 10.1144/qjegh2011-063.
- LV, Y., Nie, L., Xu, Y., Liu, F., Zheng, M., 2011. The mechanism of organic matter effect on physical and mechanical properties of turfy soil. *Chin. J. Geotech. Eng.* 33(4), 655-660.
- Mabrouk, A., Rowe, R.K., 2011. Effect of gassy sand lenses on a deep excavation in a clayey soil. *Eng. Geol.* 122(3), 292-302. DOI: 10.1016/j.enggeo.2011.06.009.
- Mesri, G., Stark, T.D., Ajlouni, M.A., Chen, C.S., 1997. Secondary compression of peat with or without surcharging. *J. Geotech. Geoenviron.* 123(5), 411-421. DOI: 10.1061/(ASCE)1090-0241(1997)123:5(411).
- Meyer, Z., 1997. Consolidation model for organic soils. *Proceedings of the ICE-Ground Improvement.* 1(4), 239-248. DOI: 10.1680/grim.1997.1.4.239.
- Moein, F., 2016. Investigating the consolidation behavior of brown coal. PhD Thesis, submitted for examination, Monash University, Melbourne, Australia.
- Moein, F., Xue, J., Dent, B., Mackay, R., 2015. Review of the Historical Data Characterising Latrobe Valley Brown Coal Consolidation behaviour. In: Eggers, M. J., Griffiths, J. S., Culshaw, M. G. & Parry, S. (eds), *Developments in Engineering Geology*. Geological Society, London, Special Publications (in press).
- Molenkamp, F., De Jager, R.R., Mathijssen, F.A., 2014. Stress measures affecting deformation of granular materials. *Vadose Zone J.* 13(5), 1-17. DOI: 10.2136/vzj2013.07.0130.
- Nageswaran, S., 1983. Effect of gas bubbles on the sea bed behaviour. PhD thesis, Oxford University, Oxford, UK.

- Pichan, S.P., O'Kelly, B.C., 2012. Effect of decomposition on the compressibility of fibrous peat: ASCE GeoCongress, pp. 4329-4338. DOI: 10.1061/9780784412121.445.
- Pietruszczak, S., Pande, G.N., 1996. Constitutive relations for partially saturated soils containing gas inclusions. J. Geotech. Eng.-ASCE. 122(1), 50-59. DOI: 10.1061/(ASCE)0733-9410(1996)122:1(50).
- Ponziani, M., Ngan-Tillard, D.J.M., Slob, E.C., 2011. A new prototype cell to study electrical and geo-mechanical properties of peaty soils. Eng. Geol. 119(1), 74-81. DOI: 10.1016/j.enggeo.2011.02.004.
- Puzrin, A.M., Tront, J., Schmid, A., Hughes, J.B., 2011. Engineered use of microbial gas production to decrease primary consolidation settlement in clayey soils. Géotechnique. 61(9), 785-794. DOI: 10.1680/geot.9.T.023.
- Rebata-Landa, V., Santamarina, J.C., 2012. Mechanical effects of biogenic nitrogen gas bubbles in soils. J. Geotech. Geoenviron. 138(2), 128-137. DOI: 10.1061/(ASCE)GT.1943-5606.0000571.
- Schreyer-Bennethum, L., 2014. Effective Stress for Saturated and Unsaturated Porous Media-A Differential Approach. Vadose Zone J. 13(5): 1-11. DOI: 10.2136/vzj2013.06.0108.
- Schuurman, I.E., 1966. The compressibility of an air/water mixture and a theoretical relation between the air and water pressures. Géotechnique. 16(4), 269-281. DOI: 10.1680/geot.1966.16.4.269.
- Skempton, A.W., 1961. Effective Stress in Soils, Concrete and Rocks. Proceedings of Conference on Pore Pressure and Suction in Soils, Butterworths, London, pp. 4-16.

- Sparks, A.D.W., 1963. Theoretical considerations of stress equations for partly saturated soils. Proceedings of 3rd African Conference on Soil Mechanics and Foundation Engineering, Salisbury, Rhodesia, pp. 215-218.
- Vlahinić, I., Jennings, H.M., Andrade, J.E., Thomas, J.J., 2011. A novel and general form of effective stress in a partially saturated porous material: The influence of microstructure. *Mech. Mater.* 43(1), 25-35. DOI: 10.1016/j.mechmat.2010.09.007.
- Wheeler, S.J., 1988. A conceptual model for soils containing large gas bubbles. *Géotechnique*. 38(3), 389-397. DOI: 10.1680/geot.1988.38.3.389.
- Xu, Y., Nie, L., Dai, S.L., Lv, Y., 2012. Analysis on Settlement of Peat Soil Foundation under Well Ditch Treatment. *Appl. Mech. Mater.* Vols. 170-173, 1093-1096.

Table 1. Physical properties of brown coal samples

Sample No.	γ_c (kN/m ³)	w_m (%)	w (%)	e
1	11.32	97.5%	137.4%	2.038
2	11.24	97.5%	136.6%	1.917
3	11.25	97.5%	133.0%	1.902

Table 2. Model parameters used for brown coal samples

Sample No.	e	e_g	e_m	E_m (MPa)	λ	S_g (%)	k (m/s)
1	2.038	1.36	73.4	26.9	0.0421	0.60%	4.0×10^{-11}
2	1.917	1.34	75.4	34.3	0.0401	0.60%	4.0×10^{-11}
3	1.902	1.38	75.4	32.6	0.0403	0.62%	4.0×10^{-11}

Table 3. Properties of peat samples in case 1

Sample No.	γ_p (kN/m ³)	ω_d (%)	w_m (%)	w (%)	e
1	11.22	45.57%	36.34%	117.01%	2.721
2	11.45	36.02%	43.65%	142.65%	3.069
3	10.45	43.23%	55.99%	272.24%	5.722
4	10.10	40.90%	69.29%	385.00%	7.115
5	9.44	50.49%	85.36%	467.55%	8.968

Table 4. Parameters used in the model for peat samples in case 1

Sample No.	σ (kPa)	e	e_g	e_m	E_m (MPa)	λ	S_g (%)	k (m/s)
1	50	2.721	0.16	1.12	5.0	0.25	2.0%	6.2×10^{-8}
2	50	3.069	0.29	1.40	3.0	0.25	3.0%	6.9×10^{-8}
3	50	5.722	0.74	2.13	2.0	0.25	3.5%	1.2×10^{-7}
4	50	7.115	1.83	4.01	1.0	0.24	4.5%	1.5×10^{-7}
5	50	8.968	5.34	8.97	0.8	0.24	5.0%	2.3×10^{-7}

Table 5. Properties of peat samples in case 2

Parameters	γ_p (kN/m ³)	w_m (%)	w (%)	e
Values	9.7	92.7%	740%	12.224

Table 6. Model parameters for peat samples in case 2

Sample No.	σ (kPa)	e	e_g	e_m	E_m (MPa)	λ	S_g (%)	k (m/s)
T10	41	12.224	11.53	20.80	0.6	0.30	4.0%	5.0×10^{-7}
T11	96	12.224	11.53	20.80	0.7	0.30	4.0%	5.0×10^{-7}
T13	96	12.224	11.53	20.80	0.8	0.25	4.0%	5.0×10^{-7}
T15	30	12.224	11.53	20.80	0.8	0.26	4.0%	5.0×10^{-7}
T18	90	12.224	11.53	20.80	0.8	0.27	4.0%	5.0×10^{-7}

Figure 1. A conceptual model of the materials

Figure 2. Three phases of the materials

Figure 3. Undisturbed Victorian brown coal samples

Figure 4. Settlement curves of brown coal sample 1 under different loading.

Figure 5. Modelling results compared with test results for brown coal sample 1

Figure 6. Modelling results compared with test results for brown coal sample 2

Figure 7. Modelling results compared with test results for brown coal sample 3

(a)

(b)

Figure 8. Modelling results compared with test results for peat samples in case 1, (a): samples 1, 2 and 3, (b) samples 4 and 5.

(a)

(b)

Figure 9. Modelling results compared with test results for peat samples in case 2, (a):

samples T10 and T11, and (b): samples T13, T15, T18 from Mesri et al. (1997).

(a)

(b)

Figure 10. Influence of the parameters to consolidation curves of (a): peat sample, and
(b): brown coal sample

Figure 11. The numerical modelled deformation of each phase during the consolidation test of Brown coal sample 1.