XII International Conference on Computational Plasticity. Fundamentals and Applications
COMPLAS XII
E. Oñate, D.R.J. Owen, D. Peric and B. Suárez (Eds)

Citation:

Zhang, L., and O'Kelly, B.C. 2013. Constitutive models for peat – a review, *Proceedings of the 12th International Conference on Computational Plasticity – Fundamentals and Applications (COMPLAS XII), Barcelona, Spain, 3rd–5th September 2013*, edited by E. Oñate, D.R.J. Owen, D. Peric and B. Suárez , International Center for Numerical Methods in Engineering (CIMNE), Barcelona, Spain, pp. 1294–1304.

XII International Conference on Computational Plasticity. Fundamentals and Applications
COMPLAS XII
E. Oñate, D.R.J. Owen, D. Peric and B. Suárez (Eds)

CONSTITUTIVE MODELS FOR PEAT — A REVIEW

LIN ZHANG* AND BRENDAN C. O'KELLY†

* Department of Civil, Structural and Environmental Engineering
Trinity College Dublin, Dublin, Ireland
e-mail: linzhang@tcd.ie, www.tcd.ie

† Department of Civil, Structural and Environmental Engineering
Trinity College Dublin, Dublin, Ireland
email: bokelly@tcd.ie, http://people.tcd.ie/bokelly

Key words: Constitutive Model, Consolidation Hypothesis, Peat, Organic Soils, Structural Anisotropy.

Abstract. This paper presents a review of the main constitutive models for peat and other highly organic soils having extremely high water content. At present, predictions of the geomechanical behaviour of such soils for design practice are mostly based on constitutive theories developed for fine-grained mineral soils. Concepts of primary consolidation and secondary compression as applied to peat are explained using the two-level structure assumption of micropores and macropores [1]. As background, the historical development of consolidation hypotheses A&B [24] regarding the concepts of primary consolidation and secondary compression is reviewed for both mineral and organic soils. Based on microscopic examinations and in-situ testing, it is generally accepted that hypothesis B is more suitable for peat. The micro-mechanical rheological model proposed by Berry and Poskitt [2] and the isotache-compression model developed by den Haan [6] were reported to have good agreement with experimental laboratory results for fibrous and amorphous peats. Attention is given to the structural anisotropy of peat material, inherent by its fibrous nature, in these constitutive frameworks.

1 INTRODUCTION

Peat has been considered as an "ordinary extraordinary material" [21] that consists of partly decomposed or undecomposed plant remnants that have accumulated under waterlogged conditions in mire. Current research on peat is still largely based on theories developed for mineral soils. However peat deforms greatly under applied loading on account of its exceptionally high water content and organic nature. Peat also has remarkably high strength compared with mineral soils at similar water content. In order to replicate observed peat behaviour, soil models developed for mineral soils are often adapted based on empirical evidence and engineering judgement. There are two types of peat models: empirical models that correlate geotechnical behaviour of peat materials with physical properties (e.g. water content, void ratio, degree of decomposition) and constitutive models based on Terzaghi's principle of effective stress. The focus of this paper is a review of constitutive models concerning stress–strain behaviour of peat and peaty soils. Empirical models are outside of the scope.

Before considering the constitutive models, it is necessary to have a comprehension of the geomechanical behaviour of peat under laboratory and in-situ conditions. For convenience of modelling, the structure of peat materials can be treated as either isotropic or anisotropic, depending on the degree of decomposition. Peat at a high degree of decomposition is considered as amorphous and can be taken as isotropic. For peat at lower states of decomposition, structural anisotropy should be taken into account in constitutive models. Yamaguchi et al. [47] found that natural fibrous peat was cross-anisotropic and Hendry et al. [20] confirmed the same finding, stating that the extent of cross-anisotropy increased with increasing fibre content.

2 HYPOTHESES A&B

The conventional terms of "primary consolidation" and "secondary compression" often cause confusion in dealing with peat. Primary consolidation is solely a process of the dissipation of excess pore water pressure, as defined by Terzaghi [45]. Secondary compression is defined as ongoing settlement associated with constant effective stress. One reasonable explanation of secondary compression for peat and other organic soils is based on the micropore and macropore concepts [1]. De Josselin de Jong [4] suggested that during primary consolidation, water is only expelled from the macropores, where the excess pore water pressure is measured. During the secondary compression stage, pore water is gradually expelled from the micropores into macropores.

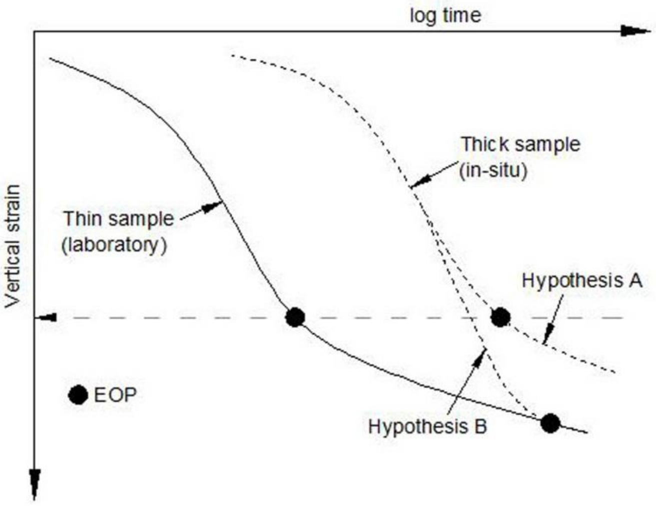

Figure 1. Effect of sample thickness with respect to creep hypotheses A & B (after [24]).

The models developed generally treat consolidation and creep compression as either simultaneous or separate processes. This division leads to two philosophies, called hypotheses A and B [22, 24]. Both hypotheses consider primary consolidation as a hydrodynamic phase in the settlement process that is controlled by the dissipation of excess pore water pressure. Hypothesis A separates strains induced from the dissipation of excess pore water pressure from those due to creep and predicts that the relationship between end-of-primary (EOP) void ratio and effective stress is the same for both laboratory and field conditions. Hypothesis B assumes that creep occurs during both the consolidation phase and under the final (constant) effective stress. An implication of the two hypotheses in terms of effective stress–void ratio is presented in Figure 1.

3 CONSOLIDATION AND COMPRESSION CONCEPTS FOR PEAT

As peat consists of the partly decomposed fragmented remains of dead plant vegetation, the two-level structure concept is a substantiated interpretation of creep for peat materials. Adams[1] described that primary consolidation of fibrous peat was considered to be due to drainage of water from the macropores and secondary compression was due to the very slow drainage of water from micropores into macropores. Dhowian and Edil [8] observed significant compression and effluent flow occurring after the dissipation of measurable excess pore water pressure, with permeability decreasing dramatically during consolidation, which supported the two-level structure possibility. Hemond and Goldman [18] observed in-situ seepage tube and auger hole tests and concluded that dramatic changes in the apparent hydraulic conductivity of peat can be explained by its large elastic storativity. Hobbs [21] stated that the consolidation of peat involves the expulsion of pore water accompanied by a structural rearrangement of the solid particles; the two processes occurring simultaneously in the early stages, but following the decline of the excess pore water pressure to a very small value, structural rearrangement and expulsion of water from micropores into macropore continue as a creep-like process.

In terms of hypotheses A and B for peat, some researchers [30, 31, 33, 34, 37] have supported hypothesis A, believing that the creep rate is controlled by total strain rate as a function of stress state and effective stress rate, indicating that no unique relationship exists between effective stress, strain and strain rate during primary consolidation. Edil et al. [10] performed different tests on Middleton fibrous peat and found an essentially unique relationship between void ratio, effective stress and rate of change of void ratio, suggesting that hypothesis A may be invalid for peat. Based on microscopic studies of fibrous peat by Landva and Pheeney [26], it is intuitively reasonable to adopt hypothesis B for peat. However, the concept that creep occurs during both the hydrodynamic and constant effective stress phases might lead to confusion; e.g. it affects the interpretation of "preconsolidation" or critical pressure [12]. Additionally, when considering that creep occurs during both primary and secondary compression stages, and that the mechanism of creep is due to structural viscosity, the overstress induced by structural viscosity may lead to an over-consolidation ratio (OCR) value of less than unity [28]. Researchers should be cautious when using primary consolidation and secondary compression concepts for peat and peaty soils, realising the underlying mechanism is different from that of the conventional understanding for mineral soils.

Two categories of models can be made depending upon whether hypothesis A or B is supported. The first category, represented by the C_α/C_c concept introduced by Mesri and his coworkers, uses a creep coefficient during the creep stage, which follows directly after the EOP consolidation. These models are generally used in 1D compression analysis for peat. Although Mesri and Godlewski [34] and Mesri and Castro [32] never stated this explicitly, it is often understood that these models follow hypothesis A [42]. The second category includes either rheological or elastic visco-plastic models which consider that creep also takes place during the hydrodynamic process. Such models mostly investigate the stress–strain–strain rate relationship in order to account for time-dependent mechanical behaviour of peat.

3.1 C_α/C_c Concept

In developing the C_α/C_c concept (e.g. refer to [34]), Mesri and his co-workers proposed that there is a unique relationship between and which holds true at all combinations of elapsed time, effective stress and void ratio for a variety of natural materials, including peats. Figure 2 shows the procedure used to compute values of the C_α/C_c ratio. Mesri and Castro [32] reported that the C_α/C_c ratio ranged 0.04–0.06 for highly organic plastic clays and 0.02–0.10 for peats.

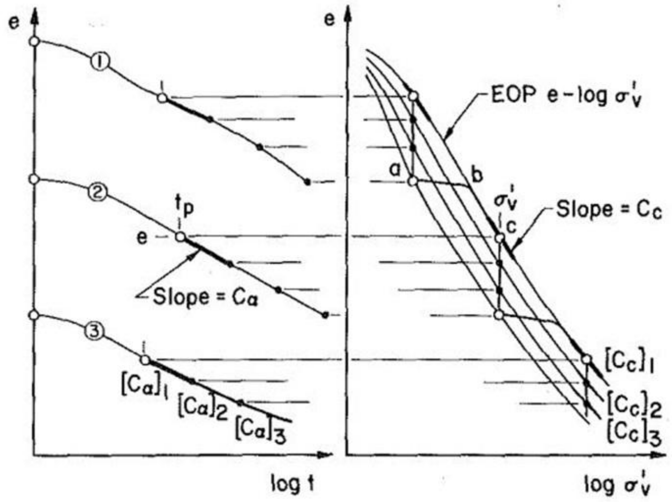

Figure 2. Calculation of C_α/C_c ratio values [34].

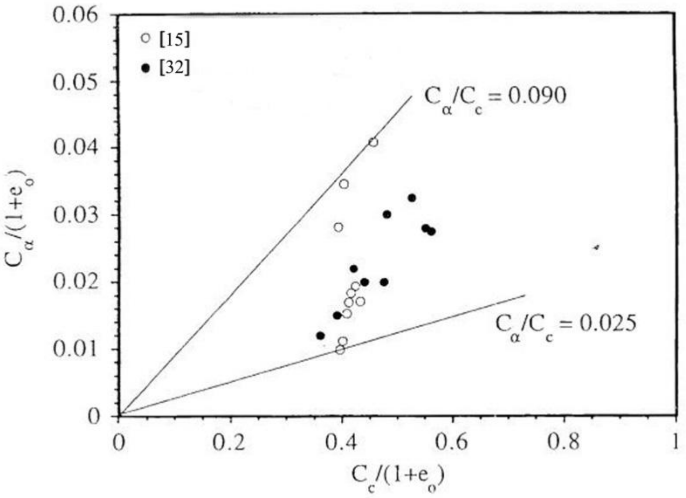

Figure 3. $C_\alpha/(1+e_o)$ and $C_c/(1+e_o)$ for Middleton fibrous peat [16].

Karunawardena [23] reported that the C_α/C_c relationship observed for Sri Lankan peat, namely $C_\alpha = 0.0341\ C_c$, agreed quite well with the $C_\alpha = 0.035\ C_c$ relationship reported for amorphous peaty clay by Mesri et al. [36]. However Fox et al. [14, 15] concluded that tertiary compression in fibrous peats makes it difficult to apply the C_α/C_c concept to these materials. By comparing their calculated results based on the procedure presented in Figure 2 against those obtained by Mesri and Castro [56] for the same experimental data (Figure 3), Fox et al. [27, 28] also showed that the determination of the C_α/C_c ratio value is subjective. Lefebvre et al. [48] reported considerable scatter in calculating the C_α/C_c ratio, although the reported mean value of 0.06 agreed well with the value of 0.052 suggested for peat soils by Mesri et al. [60].

3.2 Rheological Model

Edil [18] and Edil and Mochtar [23] used the rheological model developed by Gibson and Lo[17] to predict the settlement response of peat in both the laboratory and field tests. The rheological model can be represented by a top spring connected to a Kelvin element in series (Figure 4), with the top spring representing primary consolidation and compression of the Kelvin element representing creep, thereby indicating hypothesis B. As the model is only applicable under constant effective stress, the model fails to predict the consolidation phase accurately[25].

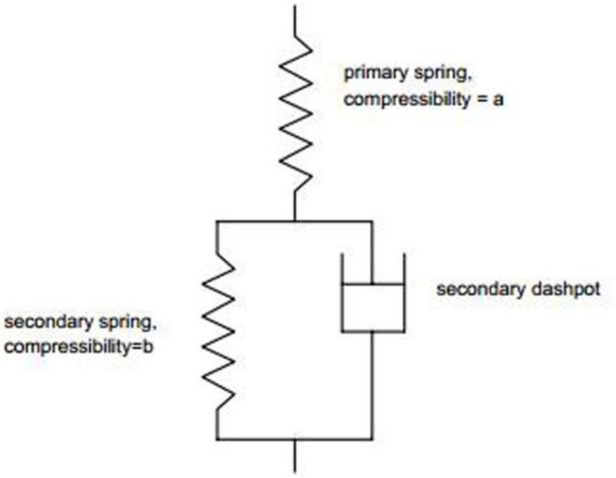

Figure 4. Rheological representation of Gibson and Lo [17] model

Berry and Poskitt [2] developed separate rheological models for amorphous and fibrous peats based on the classification made by MacFarlane and Radforth [29]. Solid particles in amorphous peat are mainly colloidal in size, with the majority of the pore water adsorbed around the grain structure. In contrast, fibrous peat essentially has an open structure, with enclosed secondary structures of mainly non-woody fine fibrous materials. Berry and Poskitt [2] suggested that the physical mechanisms controlling creep in amorphous peat are similar to those for clays; i.e. creep occurs due to the gradual readjustment of the solid particles into a more stable arrangement, following disruption of the soil skeleton, associated with compression arising from consolidation. The analogue of Gibson and Lo's [17] model was employed for amorphous peat but the springs used were nonlinear in order to simulate the soil's nonlinear compressibility. Fibrous peat was modelled based on the macropore and micropore network concept advanced by Adams [1], which was simulated using a double Terzaghi pot (Figure 5). The mathematical treatment of this model requires that only the macropore pressure in the soil element be integrated over the thickness of the soil layer in order to predict 1D consolidation behaviour. The rate of strain of the micropores is based a flow law that was postulated to describe water flow from micropores to macropores, with consideration of Darcy's law. These models have been verified by Berry and Poskitt [2] for laboratory tests on amorphous and fibrous peats.

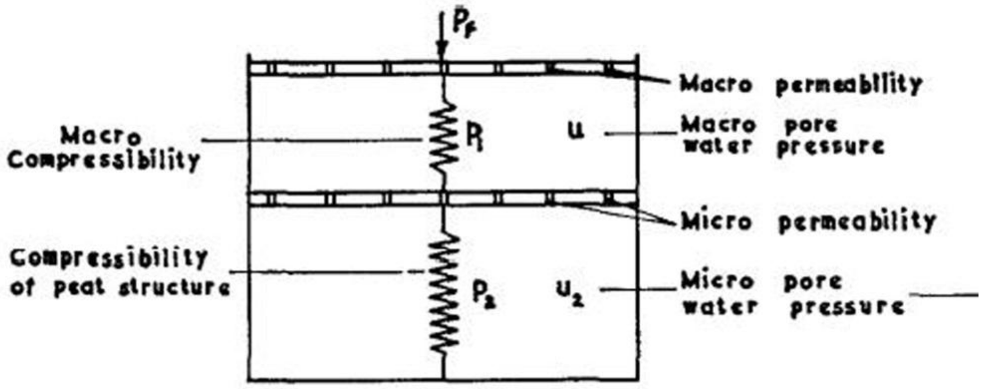

Figure 5. Rheological representation of the Berry and Poskitt [2] theory for fibrous peat

3.3 Time-line Theory and Isotache Concept

Bjerrum [3] proposed the time-line theory in order to describe the creep of clay by a series of parallel time lines in space, wherein each line represents equal periods of sustained loading. Based on time-line theory, Šuklje [44] proposed the isotache concept in order to describe rate effects on the compressibility of clayey soils. This approach states that the rate of change in void ratio is given by the prevailing void ratio and effective stress. Based on the time-line theory, Yin and Graham [48, 49, 50] proposed the elastic visco-plastic (EVP) model for clay soils. The EVP model assumes that in the normally-consolidated region, the creep strain rate for a given stress and strain state is unique and that, at a given creep strain rate, linear relationships exist between strain and logarithm of effective stress and also between strain and logarithm of creep strain rate.

Based on the EVP theory developed for clay, den Haan and Edil [7] and den Haan [6] proposed the *abc* consolidation model for 1D compression of soft clay and peat. These two models are essentially similar in that they both assume a unique relationship between strain, effective stress and creep strain rate. In natural logarithmic stress–strain space, a system of parallel lines called isotaches is assumed to exist on which the secular strain rate is constant. In the *abc* consolidation model, the total strain rate is the combination of direct strain rate (strain rate due to the changing effective stress) and creep strain rate (Eq. 1). Den Haan [5] showed that for cases involving large strain, the logarithmic small strain exceeds engineering strain and that the *abc* model fitted measured incremental oedometric compression data for soft clay and peat satisfactorily. O'Loughlin [39] adopted the *abc* model in predicting the 1D creep behaviour of bog peat and concluded that the isotache concept is valid for peat if Hencky strain and natural strain rate are used. However the *abc* model is not suitable for overconsolidated behaviour since the isotaches are neither parallel nor linear in the overconsolidated region.

(1)

3.4 PLAXIS 3D Creep Model

The 3D creep model should be a straightforward extension of the 1D creep model, but this is hampered since current 1D isotache models have not been formulated as differential equations. The Soft Soil (SS) and Soft Soil Creep (SSC) models [43, 46] implemented in the PLAXIS finite element code are proposed to deal with soft soils; e.g. near normally-consolidated clays, clayey silts and peat. These models formulate a constitutive law in differential form to solve transient or continuous loading problems. In essence, the SSC model is an isotache model. Having determined the ellipses in the *p*-*q* stress plane (Figure 6) from the modified Cam-Clay model [41], an equivalent pressure p^{eq}, in the form of Eq. 2, has been defined. The elastic part of the total strain rate employs Hook's law and the equivalent pressure p^{eq} is taken as a plastic potential function for deriving individual creep strain-rate components. Osorio Salas [40] used the SS and SSC models incorporated in PLAXIS to back-analyse vacuum consolidation test data for a pseudo-fibrous peat deposit and reported acceptable results for predicted vertical displacements, although these models overestimated the ground heave measured following removal of the vacuum pressure. The parameters of the SS and SSC models can be determined either from isotropic compression tests or oedometer testing.

(2)

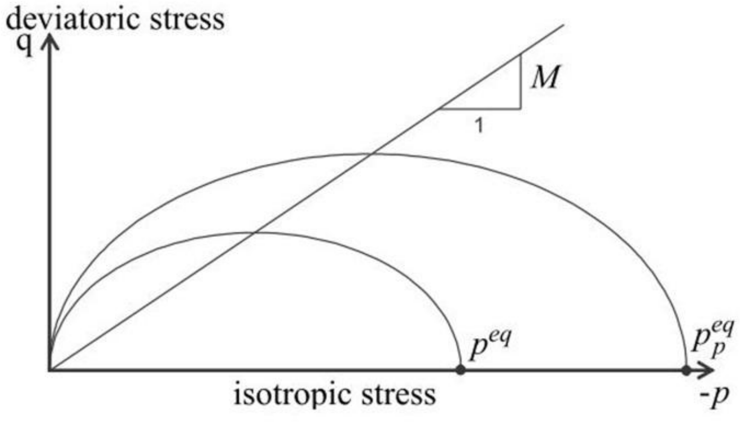

Figure 6. Diagram of p_{eq}-ellipse in the p–q stress plane.

4 STRUCTURAL ANISOTROPY

The fibrous nature of peat is one of its most distinctive properties. Farrell and Hebib [13] investigated the mechanical behaviour of fabric peat and found that specimens tested in drained triaxial compression deformed almost one-dimensionally under loading, without achieving failure as defined by peak deviatoric stress by 35% axial strain. In undrained triaxial compression tests, the pore water pressure may rapidly build up, almost reaching the applied cell pressure, thereby producing an effective lateral stress approximately equal to zero on account of the low Poisson's ratio of fabric peat [12]. O'Kelly and Zhang [38] performed drained triaxial compression tests on undisturbed, reconstituted and blended peats from the same parent material and found that the lowest Poison's ratio value measured was achieved for undisturbed peat, a slightly greater value for reconstituted peat and significant greater value for blended peat. Low Poisson's ratio values for undisturbed and reconstituted peats were attributed to lateral resistance induced by the fibres and also the tensile strength of the fibres themselves [38].

Fox and Edil [14] developed a discrete element model (DEM), FIBER, in order to account for the mechanical behaviour of the peat fibres. In this model, the peat microstructure is considered as an assemblage of deformable cellular fibres in which each fibre is composed of an irregular arrangement of bar elements. These bars have the capacity to undergo both elastic and creep deformation. Fibres can become completely separated and undergo rigid body motion. Contacts between fibres are "hard", such that no interpenetration of bodies can occur. Hence settlement occurs as a result of the deformation of fibres themselves. FIBER reportedly gives qualitatively good simulations of stress and temperature effects on creep, tertiary compression, thermal precompression and the unloading/reloading preconsolidation effect, even for a relatively simple mesh. However soil hardening occurring during compression is poorly modelled using simple meshes and a more complex mesh microstructure is necessary in order to accurately reproduce the strain hardening of fibrous peat.

Hendry [19] developed a conceptual model for the undrained response of peat based on the idea that its undrained behaviour is defined by cross-anisotropic stiffness and the strength produced by the development of tension within the peat fibres. Hendry [19] and Hendry et al. [20] considered the undrained fibre effect as cross-anisotropic elastic behaviour by adopting uniform stiffness within the horizontal plane, but different properties for the vertical direction. The anisotropic elastic model of fibrous peat incorporated the decoupled relationship between shear and volumetric responses. The pore water pressure response for the undrained condition was considered by coupling deviatoric and isochoric effects. As a result, a function of both changes in mean total and deviatoric stress is that the elastic stress path no longer follows a path of constant mean effective stress [51].

4 SUMMARY AND CONCLUSIONS

In recent decades, constitutive models for peat have mainly been adopted from conventional constitutive theories developed for fine-grained mineral soils. Developments in microscopic scanning technology have allowed researchers to investigate microscopic features of peat soils. Conceptual ideas of peat soil consolidation have been made and constitutive models for microscopic and macroscopic levels have been proposed and investigated. Reviewing recent developments, the following significant features can be identified.

a. Constitutive theories developed for mineral soils have been adjusted to consider the large strain problems typically encountered in dealing with peat. For instance, Hencky strain has been used instead of the conventional engineering strain.
b. Several plausible conceptual ideas have been proposed, such as the two-level structure concept. Micromechanical models developed on the basis of these conceptual ideas are informative However, the conceptual philosophies remain difficult to substantiate by experimental testing, and the determination of the conceptual parameters, such as

the equivalent permeability from micropores to macropores, is greatly empirical and subjective.

c. The structural anisotropy of fibrous peat has attracted considerable attention from researchers, with several approaches investigated for numerical modelling. In particular, theory for considering structural anisotropy using a simplified fibre arrangement has been developed for peat and peaty soils.

d. Recent constitutive models for peat soils are developed in partial differential form, with decoupled deviatoric and isochoric responses. Numerical analysis methods, such as finite element and discrete element methods, have been used for both 1D and 3D constitutive models.

5 ACKNOWLEDGEMENT

The first writer gratefully acknowledges an IRCSET Embark Initiative Postgraduate Research Scholarship (grant number RS/2011/271) from the Irish Research Council.

REFERENCES

[1] Adams, J.I. A comparison of field and laboratory measurement in peat. *Proc 9th Muskeg Res Conf Ontario Hydro Res Q*, (1963) **15**: 1–7.

[2] Berry, P.L. and Poskitt T.J. The consolidation of peat. *Géotechnique* (1972) **22**(1): 53–70.

[3] Bjerrum, L. Engineering geology of Norwegian normally consolidated marine clays as related to settlements of buildings. *Géotechnique* (1967) **17**(2): 81–118.

[4] De Josselin de Jong, J. Consolidation models consisting of an assembly of viscous elements or a cavity channel network. *Géotechnique* (1968) **18**(2): 195–228.

[5] Den Haan, E.J. Stress-independent parameters for primary and secondary compression. *Proc 13th Int Conf Soil Mech Found Eng*, New Delhi, (1994) **1**: 65–70.

[6] Den Haan, E.J. A compression model for non-brittle soft clays and peat. *Géotechnique* (1996) **46**(1): 1–16.

[7] Den Haan, E.J. and Edil, T.B. Secondary and tertiary compression of peat. *Advances Underst Model Mech Behav Peat*, Balkema, Rotterdam, (1994): 49–60.

[8] Dhowian, A.W. and Edil, T.B. Consolidation behavior of peats. *Geotech Test J — ASTM*, (1980) **12**(3): 105–114.

[9] Edil, T.B. Use of preloading for construction on peat. *Proc 13th Minnesota Conf Soil Mech Found Eng*, St. Paul, Minnesota, (1982): 125–140.

[10] Edil, T.B., Fox, P.J. and Lan, L.T. Stress-induced one-dimensional creep of peat. *Advances Underst Model Mech Behav Peat*, Balkema, Rotterdam, (1994): 3–18.

[11] Edil, T.B. and Mochtar, N.E. Prediction of peat settlement. *Proc Symp Sediment Consol Model*, ASCE, San Francisco, (1984): 411–424.

[12] Farrell, E.R. Organic/peat soils. *In ICE Man Geotech Eng (Burland J, Chapman T, Skinner H and Brown M (eds)*. ICE Publishing, London. (2012) **1**: 463–477.

[13] Farrell, E.R. and Hebib, S. The determination of the geotechnical parameters of organic soils. *Probl Soils (eds. Morito & Mitachi)*. Balkema, Yanagisawa, (1998): 33–36.

[14] Fox, P.J. and Edil, T.B. Micromechanics model for peat compression. *Advances Underst Model Mech Behav Peat*, Balkema, Rotterdam, (1994): 159–166.

[15] Fox, P.J., Edil, T.B. and Lan, L.T. Cα/Cc concept applied to compression of peat. *J Geotech Eng —ASCE* (1992) **118** (8): 1256–1263.

[16] Fox, P.J., Edil, T.B. and Lan, L.T. Closure to "Cα/Cc concept applied to compression of peat" by Fox PJ, Edil TB, Lan LT (August, 1992, Vol. 118, No.8). *J Geotech Eng — ASCE* (1994) **120**(4): 767–770.

[17] Gibson, R.E. and Lo, K.Y. A theory of consolidation for soils exhibiting secondary compression. *Norw Geotech Inst Publ* (1961) **41**: 1–16.

[18] Hemond, H.F. and Goldman, J.C. On non-Darcian water flow in peat. *J Ecol* (1985) **73**(2): 579–584.

[19] Hendry, M.T. The Geomechanical Behaviour of Peat Foundations Below Rail-track Structures. *Dissertation*, University of Saskatchewan, (2011).

[20] Hendry, M.T., Sharma, J.S., Martin, C.D. and Barbour, S.L. Effect of fibre content and structure on anisotropic elastic stiffness and shear strength of peat. *Can Geotech J* (2012) **49**(4): 403–415.

[21] Hobbs, N.B. Mire morphology and the properties and behaviour of some British and foreign peats. *Q J Eng Geol* (1986) **19**(1): 7–80.

[22] Jamiolkowski, M., Ladd, C.C., Germaine J.T. and Lancellotta R. New developments in field and laboratory testing of soils: general report. *Proc 11th Int Conf Soil Mech Found Eng*, San Francisco, (1985) **1**: 57–153.

[23] Karunawardena, W.A. Consolidation Analysis of Sri Lankan Peaty Clay Using Elasto-viscoplastic Theory. *Dissertation*, Kyoto University, (2007).

[24] Ladd, C.C., Foott, R., Ishihara, K., Schlosser, F. and Poulus, H.G. Stress-deformation and strength characteristics. *Proc 9th Int Conf Soil Mech Found Eng*. Tokyo, (1977) **1**: 421–494.

[25] Lan, L.T. A Model for One-dimensional Compression of Peat. *Dissertation*, University of Wisconsin, (1992).

[26] Landva, A.O. and Pheeney, P.E. Peat fabric and structure. *Can Geotech J* (1980) **17**(3): 416–435.

[27] Lefebvre, G., Langlois, P., Lupien, C. and Lavalle, J.G. Laboratory testing and in situ behavior of peat as embankment foundation. *Can Geotech J* (1984) **21**(2): 322–337.

[28] Leoni, M., Karstunen, M. and Vermeer, P.A. Anisotropic creep model for soft soils. *Géotechnique* (2008) **58**(3): 215–226.

[29] MacFarlane, I.C. and Radforth, N.W. A study of the physical hebaviour of peat derivatives under compression. *Proc 10th Muskeg Res Conf — NRC* (1965): 159–164.

[30] Mesri, G. Primary compression and secondary compression. *Geotech SP—ASCE* (2003) 119: 122–166.

[31] Mesri, G. Discussion of "Effect of friction and thickness on long-term consolidation behaviour of Osaka Bay clays" by Watabe, Udaka, Kobayashi, Tabata and Emura. 2008. *Soils Found* (2009) **49**(5): 823–824.

[32] Mesri, G. and Castro, A. Cα/Cc concept and K_0 during secondary compression. *J Geotech Eng — ASCE* (1987) **113**(3): 230–247.

[33] Mesri, G. and Choi, Y.K. The uniqueness of the end-of-primary (EOP) void ratio-effective stress relationship. *Proc 11th Int Conf Soil Mech Found Eng,* San Francisco, (1985) **2**: 587–590.

[34] Mesri, G. and Goldewski, P.M. Time- and stress-compressibility interrelationship. *J*

Geotech Eng — ASCE 103(GT5) (1977): 417–430.

[35] Mesri, G. and Godlewski, P.M. Closure of "Time and stress-compressibility interrelationship" by Mesri and Godlewski, 1977. *J Soil Mech Found Div — ASCE 105 (GT1)* (1979): 106–113.

[36] Mesri, G., Stark, T.D., Ajlouni, M.A. and Chen, C.S. Secondary compression of peat with or without surcharging. *J Geotech Geoenviron* (1997) **123**(5): 411–421.

[37] Mesri, G. and Vardhanabhuti, B. Closure of "Secondary compression" by Mesri and Vardhanabhuti, 2005. *J Geotech Geoenviron Eng* (2006) **132** (6): 817–818.

[38] O'Kelly, B.C. and Zhang, L. Consolidated-drained triaxial compression testing of peat. *Geotech Test J* (2013) **36**(3): 310–321, doi: 10.1520/GTJ20120053.

[39] O'Loughlin, C.D. The One-dimensional Compression of Fibrous Peat and Other Organic Soils. *Dissertation*, University of Dublin, Trinity College, (2001).

[40] Osorio Salas, J.P. Vacuum Consolidation Field Test on a Pseudo-fibrous Peat. *Dissertation*, University of Dublin, Trinity College, (2012).

[41] Roscoe, K.H. and Burland, J.B. On the generalized stress-strain behaviour of 'wet' clay, *Engineering Plasticity (eds. Heyman J, Leckie FA)*, Cambridge University Press, (1968): 535–609.

[42] Schiffman, R.L., Ohta, H. and Pradhan, T.B.S. Discussion. *Proc Int Symp Comp Consol Clayey*, Balkema, Rotterdam, (1995): 1049–1054.

[43] Stolle, D.F.E., Vermeer, P.A. and Bonnier, P.G. Consolidation model for a creeping clay. *Can Geotech J* (1999) **36**(4): 754–759.

[44] Šuklje, L. The analysis of the consolidation process by the isotaches method. *Proc 4th Conf Soil Mech Found Eng*, London, (1957) 1: 200–206.

[45] Terzaghi, K. *Theoretical Soil Mechanics*. John Wiley & Sons, New York, (1942).

[46] Vermeer, P.A. and Neher, H.P. A soft soil model that accounts for creep. *Beyond 2000 in Comput Geotech: 10 years of Plaxis Int (ed. Brinkgreve RBJ)*, Balkema, Rotterdam, (1999): 249–261.

[47] Yamaguchi, H., Ohira, Y., Kogure, K. and Shigeru, M. Undrained shear characteristics of normally consolidated peat under triaxial compression and extension conditions. *Soils Found* (1985) **25**(3):1–18.

[48] Yin, J.H. and Graham, J. Viscous-elastic-plastic modelling of one-dimensional time-dependent behaviour of clays. *Can Geotech J* (1989) **26**(2): 199–209.

[49] Yin, J.H. and Graham, J. Equivalent times and one-dimensional elastic visco-plastic modelling of time-dependent stress-strain behaviour of clays. *Can Geotech J* (1994) **31**(1): 42–52.

[50] Yin, J.H. and Graham, J. Elastic visco-plastic modelling of one-dimensional consolidation. *Géotechnique* (1996) **46**(3): 515–527.

[51] Wood, D.M. *Soil Behaviour and Critical State Soil Mechanics*. Cambridge University Press, Cambridge, (1990).