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Geotechnical Challenges in Numerical Modelling of Sarawak Fibrous Peat

Seneviratne K. G. H. C. Nimal[1,*]

[1]Department of Civil Engineering, Faculty of Engineering, University of Peradeniya, 20400 Peradeniya, SRI LANKAN.

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Abstract: In Sarawak, about 13% of the total land area is covered with recent peat deposits. A complex mechanism of plant growth and peat accumulation with time has led to formation of flat topped peat domes. Dome centre consists of highly fibrous ombrogeneous peat. Topogeneous peat found in the fringes of peat domes and in interior floodplains, consists of a mixture of decomposed plant matter and fine clastic sediments. Mechanical behaviour of fibrous peat is influenced by the arrangement of fibre. The present study shows that fibrous peat as well as temperate peat conforms to a unique dry density - moisture content relationship. A preliminary study has been carried out in developing a cellular model of fibrous peat. The finite element analysis of time dependent stress strain behaviour performed using this model shows interesting results and promise of application in understanding the behaviour of fibrous peat.

Keywords: Fibrous peat, dry density, moisture content, finite element analysis, consolidation

1. Introduction

Peat results from the decomposition of plants and other organic matters, often under anaerobic conditions. Tropical peats are essentially products of decomposed trees and tree remnants unlike their temperate zone cousins derived mainly from sphagnum and sedges. However, these differences are not precise, as for example low moor peat in temperate regions is similar to tropical peat in many ways. Heavy rainfall and other beneficial climatic conditions make tropical peat to grow at a faster rate than temperate peat. Geologically, tropical peat deposits are recently formed during Holocene period. Over 50% of the world deposits of tropical peat are known to occur in South East Asia (Andriesse [2]). According to Mutalib et al. [16], over 10% of the total land mass in Sarawak contains deep peat deposits as classified according to a modified USDA (United States Department of Agriculture) classification system adopted for Sarawak conditions. These deposits have formed during last 5000 years with the rise of the sea level after the last ice age.

In Sarawak, peat deposits occur both in coastal plains and in inland low lying areas. The development pressures through construction related to expansion of townships and related infrastructure, and the increase of land use for agriculture and other purposes, have made considerable impact on peat deposits. The water regime within peat has been affected due to change in ground water table and pollution associated with human development. This paper will describe difficulties of numerically modelling fibrous peat as an engineering material. It explores the reliability of physical and engineering parameters which can be used to describe the fibrous peat and explore the use of cellular models in performing finite element analysis aimed at understanding the fundamental time dependent behaviour of fibrous peat.

2. Formation and Morphology

The formation and nature of Sarawak peat has been well researched and documented by geologists, geotechnical engineers, and agricultural soil scientists (e.g. Anderson [1], Andriesse [2], Tie and Esterle [22], Singh et al. [18] and, Staub and Gastaldo [20]). Anderson [1] identified two distinct groups of organic deposits in Sarawak, namely basin peats and valley peats. Valley peats occur in poorly drained interior valleys and river floodplains; they are often mixed with clastic sediments or interlaced with sediment soil formations, and are well decomposed aided by frequent fluctuations in the water table. Valley peats are geologically termed as topogeneous peat. Topogeneous peat is also found in the fringes of basin peat formations which have been exposed to flooding.

Basin peats are found in lowland coastal swamps usually bordered by a levee of mineral soils which helps retention of water. However, unlike bog peat which is formed under aquatic conditions, Sarawak basin peats have formed largely under terrestrial conditions in low lying poorly drained areas, and not under aquatic conditions (Tie and Esterle [22]). They are dome shaped

* *Corresponding author: nimals@pdn.ac.lk*

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with thickness varying from centre to edges due to drainage conditions and nutrient availability prevailed at different parts of the dome during the history of about 4000 years since inception. In the initial stages the rate of growth is larger at the centre of the dome than elsewhere, but as the dome height increases, lack of water and nutrients at the centre lead to a reduction of rate of peat formation at the centre. This results in overall flattening of the dome and spreading of the dome near the outer rim. The thickness of a peat dome is large and 20 m thick deposits are commonly encountered today in Sarawak peat swamps (Tie and Esterle [22]).

3. Classification of Sarawak Peat

Agriculturists tend to classify the peat domes based on surface organic layers and the plants growing on them. Travelling from the centre of the dome towards the edges, Alan, Padan Alan and Mixed peat Swamp Forest are encountered in succession (Melling [15]). The mixed peat swamp forest contains the most decomposed peat formed and peat here is less woody than in other areas. The woodiest peat is encountered in Alan areas which are well drained. In the flatter central part of the dome, Padan Alan peat has less woodiness, but peat here is the least decomposed, almost raw, containing highly fibrous peat.

According to ASTM and Malaysian Standards a soil having an organic content greater than 20% is called an organic soil. Peat is defined as an organic soil with an organic content greater than 75%. Organic content of a soil is usually characterised by loss on ignition defined as the percentage weight loss of a sample upon burning in an oven when the temperature is increased from 105˚ C to 550˚ C. USDA classification of Peat is based on fibre content measured by percentage by weight of organic particles retained on a 0.15 mm diameter sieve. Peat with fibre content greater than 65% is called Fibric peat. When fibre content of peat is less than 65%, it is called Hemic or Sapric peat depending on whether the fibre content is greater or smaller than 33% respectively. More decomposed peats are Sapric and are therefore, amorphous. Sapric peats are found in well drained areas or in mixed peat swamps. Ombrogenous peats are usually Fibric, in contrast, topogeneous peats tend to be mostly amorphous.

A method used for classification of peat in the field is the Von Post scale (Von Post [23]). Based on the colour and the clarity of fluid exuded from a peat sample squeezed in the hand between fingers, a scale of H1 to H10 is used to classify the degree of humification of the sample tested. According to the scale, H1-H3 denote Fibric or fibrous peat, H4-H6 Hemic or moderately decomposed peat and H7-H10 Sapric or amorphous peat. Classifications based on conventional methods for inorganic soils such as particle size distribution and Atterberg limits are of little help in identifying the nature of fibrous peat. However, in amorphous or well decomposed peat they may be more applicable. Peat particles are very fragile and break very easily. The behaviour of peat may be substantially influenced by the arrangement of fibres which are elongated rather than spherical in shape and therefore, particle size distribution based on equivalent diameter may be of little help in understanding the mechanical behaviour of peat, particularly fibrous peat.

4. Physical Properties

Physical properties such as organic content, specific gravity, moisture content and dry unit weight of Sarawak peat have been reported by a number of researchers in the literature (e.g. Singh et al. [18], Lam [13], Lam [14], Kaniraj and Joseph [10], Huat [8], Kolay et al. [12], and Taib and Ismail [21]). There are also data on Sarawak Peat reported by agricultural scientists but mostly on samples taken from the top soil at depths less than 1.5 m below the ground surface. Some of the above mentioned researchers have also proposed empirical relations among physical properties; comparisons have also been made with similar correlations existing in the literature for peat from temperate regions.

Based on experimental data on temperate peat Skempton and Petley [19] proposed a relationship between the specific gravity of an organic soil and organic content (OC). This relationship is based on the simple volume mass relationship of a mixture of organic and inorganic compounds given by,

$$\frac{1}{G_s} = \frac{OC}{G_{or}} + \frac{(1-OC)}{G_{inor}} \tag{1}$$

where, G_s specific gravity of peat, G_{or} specific gravity of organic particles, and G_{inor} specific gravity of mineral constituents. Den Haan [4] found very good agreement with the relationship given by equation (1) above for a wide range of existing data on Dutch organic soils. Noting that the loss on ignition (N) can be used as equal to organic content without losing much accuracy, Den Hann obtained values for parameters G_{or} and G_{inor} for temperate peat equal to 1.365 and 2.695 respectively. Considering the possibility of higher Lignin content in tropical peat than in temperate peat, Den Hann stated that G_{or} for tropical peat is likely to be less than 1.365.

Fig. 1 illustrates the data for a tropical peat from West Malaysia given by Duraisamy et al. [5]. The observations fit a regression line almost parallel to the Den Hann relationship with G_{or} and G_{inor} values of 1.34 and 2.64 respectively; these values are only marginally lower than the values found by Den Haan for temperate peat. Therefore, the effect of Lignin content does not appear to be large enough to affect the specific gravity relationship of West Malaysian peats. Based on the data given by Taib and Ismail [21] from the undergraduate and postgraduate work at Universiti Malaysia, Sarawak, Sarawak peat has a very high organic content of 90% – 95%; G_{or} based on an assumed G_{inor} of 2.67 ranges between 1.21 – 1.32 with an average value of 1.27. Unlike data from Peninsular Malaysia, Sarawak data conforms to Den Haan's proposition that G_{or} is smaller for tropical organic peat than in temperate peat.

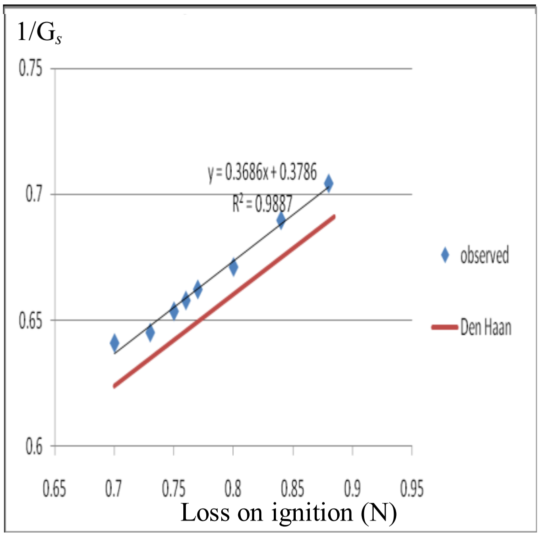

Fig. 1 Relationship between Loss on ignition and specific gravity of peat. Data from Duraisamy et al. [5].

Den Hann [4] also proposed an empirical relation between the dry density and moisture content of Dutch organic soils and peat based on available data as

$$\rho_d = 0.872 * (w + 0.317)^{-0.982} \quad (2)$$

where, ρ_d is the dry density in g/cm^3 and w, the moisture content. Den Haan stated that data for peat from several other places in Europe and United States also agree with this relationship. Duraisamy et al [5] found that their experimental data on West Malaysian peat is not well represented by Den Hann relationship and proposed a new empirical formula,

$$\rho_d = 22.422(100w)^{-0.804} \quad (3)$$

The volume weight relationship based on voids ratio diagram in classical soil mechanics gives:

$$\gamma_d = \frac{\gamma_w}{\frac{1}{G_s} + \frac{m}{s}} \quad (4)$$

where, γ_w is the unit weight of water, and s the degree of saturation. Assuming that peat soil is saturated with a value of G_s equal to 1.4, the above expression becomes,

$$\gamma_d = \frac{\gamma_w}{0.7 + m} \quad (5)$$

This relationship, Equation (5), is shown in Fig. 2 along with Den Hann relationship, Equation (2), and Duraisamy et al. formula, Equation (3) and available data. Apart from the data given above, data from Sarawak Kuching and Sibu areas given by Lam [13] and [14] are also plotted in Fig. 2. In the case of data from Duraisamy et al. [5] moisture content values are recalculated here using the reported values of specific gravity, dry density, and bulk density. This was done as Duraisamy's reported moisture content values appear to be inconsistent with their other data.

As seen from Fig. 2, there is little difference between the Den Haan relationship, Equation (2) and Equation (5). Equation (4) is insensitive to the value of specific gravity of peat at large moisture contents when moisture content is greater than 500%. This is seen from the Table 1 which gives the variation of dry density of saturated peat with moisture content when specific gravity varies from 1.2 to 1.6. There is no significant difference (less than 2.5%) in the calculated dry density when the specific gravity is varied from 1.2 to 1.6. This is the reason for temperate peat and tropical peat from different parts of the world to conform to the same dry density - moisture content relationship.

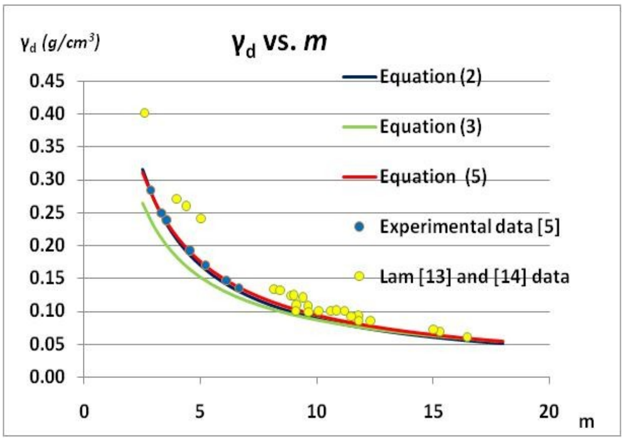

Fig. 2 Dry Density - Moisture Content relationship for tropical peat.

5. Vertical Stress Distribution with Depth

Sarawak peat deposits have very high moisture contents ranging from 500% to 1500%. Ombrogenous peat which is more fibrous than topogenous peat is likely to have a higher moisture content. Table 2 gives the dry density and saturated bulk density of peat calculated from classical soil mechanics formula assuming a G_s value of 1.4.

Table 1 Influence of specific gravity on variation of dry density of saturated peat with moisture content

Moisture Content	Dry Density (g/cm^3)		
	Gs = 1.2	Gs=1.4	Gs=1.6
5	0.171	0.175	0.178
7.5	0.120	0.122	0.123
10	0.092	0.093	0.094
12.5	0.075	0.076	0.076
15	0.063	0.064	0.064

Given also in the Table are the effective vertical stresses at 5, 10, 15 and 20 m depths calculated assuming that the moisture content of the peat is uniform throughout the layer and the water table is at the ground surface. Given the very low unit weight of Sarawak peat at high moisture content these assumptions are not unreasonable. The effective vertical stress of fibrous peat at 20 m depth for the moisture content range of 500% to 1500% varies from 10 kN/m^2 to 3.6 kN/m^2 (Table 2). Under similar conditions the effective vertical stress in a typical layer of saturated clay of bulk density = 18 kN/m^3 at 20 m depth, is approximately 160 kN/m^2. The low insitu effective stresses in natural peat ground make peat a very weak engineering material, one with low shear strength and high compressibility.

Table 2 Effective Vertical Stress Distribution with Depth

Depth Below Ground Surface (m)			5	10	15	20
Moisture Content	Dry Density (g/cm^3)	Saturated Bulk Density (g/cm^3)	Effective Vertical Stress (kN/m^2)			
5	0.175	1.050	2.45	4.90	7.36	9.81
7.5	0.122	1.035	1.71	3.41	5.12	6.82
10	0.093	1.027	1.31	2.62	3.92	5.23
12.5	0.076	1.022	1.06	2.12	3.18	4.24
15	0.064	1.018	0.89	1.78	2.68	3.57

6. Compressibility and Settlement

Peat ground will experience settlement due to three factors, namely deterioration, compaction and consolidation. Peat is an unstable material and will undergo continuous deterioration with time, particularly when it is above the water table and under aerobic conditions. Therefore, any lowering of ground water table will accelerate the rate of deterioration with more peat being exposed to the atmosphere. The deteriorating peat will crumble and compact leading to further settlement; the presence of surcharge if any will cause or aggravate the particle breaking process.

Long-term subsidence of peat deposits due to these effects has been observed in Sarawak as well as in other parts of Malaysia (e.g. Mutalib et al. [16]); long- term subsidence rates in the order of 5 cm/year have been observed. In addition to this long term deterioration, fluctuations in water table and/or surcharge loading will induce excess pore pressures in peat, and with dissipation of the pore pressures peat will consolidate. Peat will undergo considerable secondary settlements in addition to primary settlement under consolidation.

Due to difficulty of sampling and testing, little data is available on the consolidation properties of fibrous peat. Gofar and Sutejo [7] obtained a compression index (C_c) of 3.15 for a fibrous sample from a West Malaysian peat deposit thicker than 5 m using Rowe cell apparatus. Duraisamy et al [5] reported C_c values ranging from 1.795 to 2.75 for sapric – fibric samples of a West Malysian peat deposit. Huat [8] gives a range of 1-3 for compression index of West Malaysian and Sarawak Peat (fibrous and amorphous) from available data. Compression index data available for amorphous peat from Sarawak as given by Khing [11] is 1.05 to 1.64. Using the classical compressibility theory formulated by Terzaghi, the normalised settlement due to a surcharge loading of a uniform normally consolidated peat deposit can be approximately expressed as,

$$\frac{\Delta H}{H} = \frac{C_c}{1+e_m} Log_{10} \frac{\sigma'_m + \Delta\sigma}{\sigma'_m} \qquad (6)$$

where, ΔH is the total settlement due to surcharge $\Delta\sigma$, H is thickness of the peat layer, while σ'_m and e_m are the effective vertical sand voids ratio at the middle of the deposit respectively.

Table 3 shows the normalised settlement (settlement per unit thickness) of a uniform peat deposit divided by C_c due to application of a surcharge loading; the moisture content at the middle of the deposit is assumed to be ranging from 500% to 1500% an initial effective stress of 1 kPa and surcharge loading varying from 1 to 50 kPa.

It is interesting to see how the normalised settlement varies with the moisture content. For a given value of C_C and a specified surcharge, higher initial moisture content leads to lower settlement. Since this is unusual as higher moisture content should lead to more settlement this is possible only if C_c also increases with the moisture content. Therefore, a fibrous peat which is having higher moisture content is likely to have a higher C_c value than a hemic or sapric soil with lower moisture content.

Table 3 Normalised Settlement of a Peat Deposit under a Surcharge Load

Moisture Content at Middle of Layer	5.0	7.5	10.0	12.5	15.0
Stress Increase (kPa)	Normalised Settlement of Layer/C_c				
1	0.038	0.026	0.020	0.016	0.014
10	0.130	0.091	0.069	0.056	0.047
20	0.165	0.115	0.088	0.071	0.060
50	0.213	0.148	0.114	0.092	0.078

Due to low insitu effective stress of peat, lowering of the water table even by few fractions of a meter may increase the effective stresses substantially and induce considerable consolidation settlement. Therefore, water table in peat ground should be maintained at the same level as much as possible. A rise in the water table above the previous minimum level can make a peat deposit over consolidated so that repeated fluctuations will only induce settlements which are only about 15 – 20% of the first time settlements. This is because the reloading or swelling compression index is about one sixth of normal compression index. When the settlements are excessive, classical Terzaghi analysis based on small strain theory is no longer applicable and formulations based on the theory of finite strain consolidation (e.g. Gibson et al. [6]) should be considered.

7. Measurement of Moisture Content

Pui et al. [17] investigated the effect of sampling on the measurement of moisture content of fibrous peat in the field. The undisturbed peat samples were obtained from Matang area in Sarawak using a CBR cylindrical mould at a depth of about 0.5 m from the ground surface. The samples indicated a degree of humification of H4 on the Von Post scale. The moisture content of the sample, measured after resaturation in the laboratory, was 374%. Thereafter, the sample was allowed to freely drain under gravity and loss of moisture in the sample was recorded with time. Fig. 3 illustrates the behaviour in three tests conducted, showing moisture loss with time. The samples which had moisture of about 2 kg after resaturation lost about 0.35 kg of water, a loss of moisture content of 17.5%, within the first five minutes of draining. This is probably due to draining of macropores within the sample. Thereafter, the rate of moisture loss was slow, about 0.0031 kg/min.

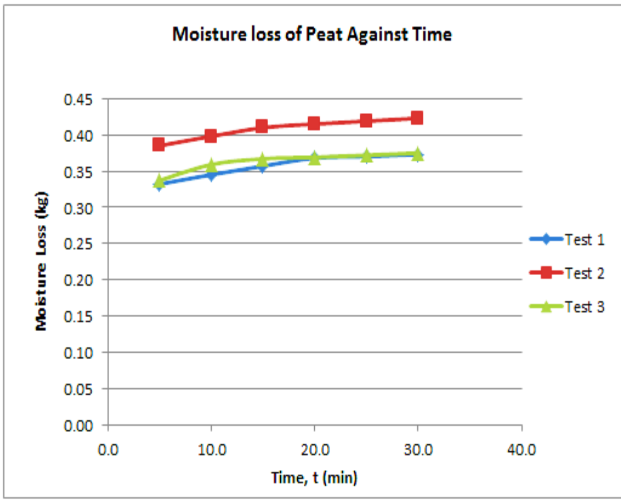

Fig. 3 Moisture loss of peat during sampling.

The substantial loss of moisture during draining is a serious concern for moisture content measurement of fibrous peat. The problem might be even more acute in other peat, more fibrous than those tested above, having field moisture contents well over 1000%. Therefore, it is certainly more accurate to resaturate the samples of fibrous peat in the laboratory before determining the moisture content. The saturated permeability of the peat samples tested by Pui et al. [17] was small, in the range of 1.2 – 0.6 $\times 10^{-6}$ cm/s. Therefore, except for the initial moisture loss due to macropores, the movement of water through micropores appear to be very slow.

8. Finite Element Modelling

To understand the mechanical behaviour of fibrous peat conceptually, a one dimensional model representing two materials forming a layered structure was formulated by the author (Fig. 4a). This model can be readily extended to two dimensions to form a honeycomb structure (Fig. 4b). Material 1 represents macropores which is assumed to have a high permeability and probably low stiffness. Material 2 represents micropores having low permeability and probably higher stiffness. The engineering properties of material 1 and 2 may be selected from experimental data by modelling simple problems such as 1-D consolidation.

1-D consolidation of fibrous peat is numerically modelled here using the finite element package AFENA version 6.0 developed by Centre for Geotechnical Research, University of Sydney, Australia (Carter and Balaam [3]). AFENA is capable of solving stress- strain problems with fully coupled consolidation. The analysis was performed with 8 noded quadrilateral elements. Plane strain linear elastic – Mohr Coulomb model was used to analyse the problem. Mohr- Coulomb parameters were set arbitrarily at high values to produce linear elastic behaviour at all points. The material properties used in the analysis are given in Table 4.

Fig. 4(a) 1-D conceptual model of fibrous peat.

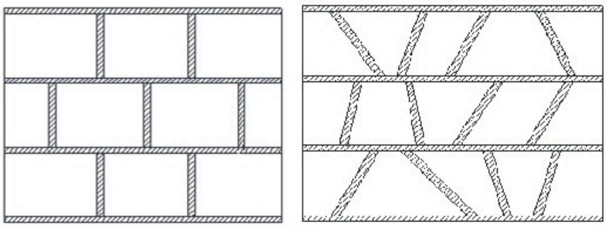

Fig. 4(b) 2-D conceptual models (brick and random).

Table 4 Material Properties for Analyses

Material	Modulus of elasticity E (kN/m^2)	Poisson ratio, ν	Permeability mm/s
1	100	0.3	74.29
2	100	0.3	0.7429

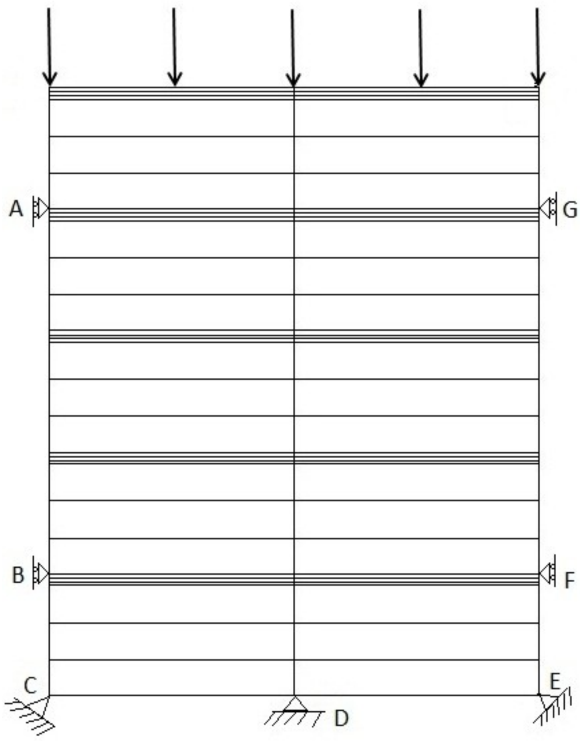

Fig. 5 Finite element mesh.

Fig. 5 shows the finite element mesh used for the analysis with boundary conditions. The thin elements with thickness 1/165 m are made of material 2; thick elements with thickness 1/16.5 m are made of material 1. The material 1 represents basically the pore water, the main constituent of macropores. Five alternating layers of material 1 and 2 are each represented by six geometrically equal elements. At the beginning of the analysis it is assumed that there are no stresses within the elements. The consolidation due to application of 1 kN/m^2 stress on the ground surface is modelled in the analyses.

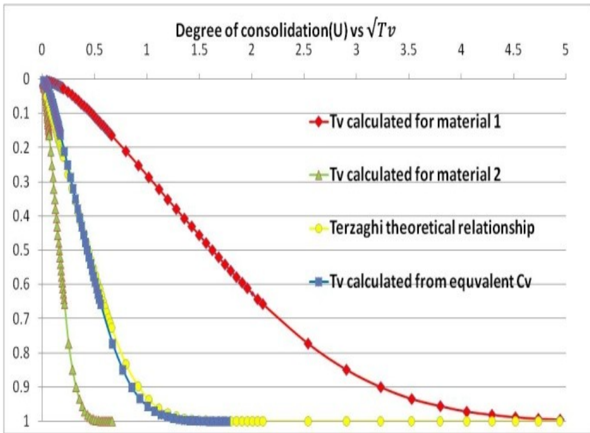

Fig. 6 Analytical Degree of Consolidation with Time.

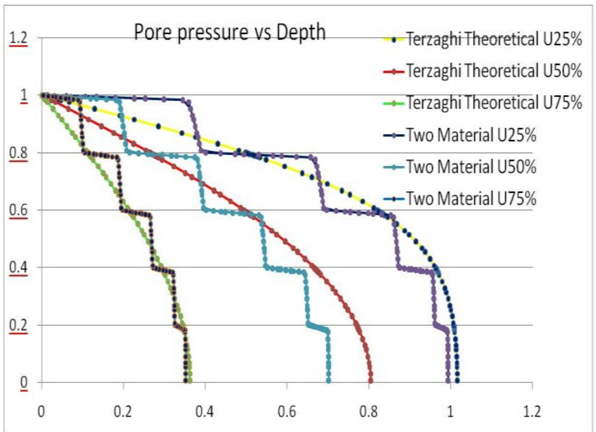

Fig. 7 Pore Pressure Isochrones.

In the analysis layers of material 1 and 2 were modelled as shown in Fig. 5 and the surface settlement - time relationship obtained is presented in Fig. 6. The results are presented in normalized form with settlement given as degree of consolidation (U) and root time of consolidation transformed to root of time factor, $(T_v)^{1/2}$. In determining root time factor, $(T_v)^{1/2}$, calculations were carried out using the coefficient of consolidation C_v of materials 1 and 2 leading to two graphs on Fig.6. The classical Terzaghi theoretical U, $(T_v)^{1/2}$ relationship for 1-D consolidation was also plotted on Fig. 6 along with the analytical results matched to theoretical relationship by selecting an equivalent coefficient of consolidation C_v.

Table 5 compares the coefficient of consolidation for material 1 and 2 with the equivalent C_v calculated in the above manner.

Table 5 Comparison of C_v

Material	C_v (m^2/s)
1	1.00
2	0.01
Equivalent	0.07

Replacement of nearly 9% of the sample height from material 1 to material 2 which has a C_v of 1/100 times that of material 1, has reduced the effective C_v by about 14 times. This illustrates the possible impact of micropores on drastically reducing the coefficient of consolidation of fibrous peat. The pore pressure distribution with depth at degree of consolidation, U at 0.25, 0.50 and 0.75 in the two layer finite element analysis and in Terzaghi theoretical relationship, are illustrated in Fig. 7. The distributions look similar except for the higher pore pressure gradient developed in layers of material 2 having low permeability.

The future work in the development of a suitable cellular model for fibrous peat should include matching of actual behaviour in field road embankments (e.g. Junaidi [9]). Also percolation tests in fibrous peat can be conducted in the laboratory to observe time dependent water outflow from large undisturbed field specimens (samples taken using CBR or permeability moulds). The latter results may be used to obtain material parameters for the analysis. In two dimensional analyses more complex cellular models shown in Fig. 4b may be considered.

9. Conclusions

The existing data on fibrous peat has shown that dry density and moisture content relationship for fibrous peat may be presented in a simple form and would only involve moisture content as a critical parameter. The determination of moisture content in the field should take into account the possibility of moisture loss during sampling. This may be rectified somewhat by resaturating the field samples before measuring moisture content. Cellular models may be considered in modelling the micropores and macropores in fibrous peat. These models show promise of application to analytically examine the time dependent behaviour of fibrous peat.

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