Geotechnical properties and microstructural characteristics of Northeast Indian peats

A. Paul[1] and M. Hussain[2]

[1]Doctoral Scholar in Geotechnical Engineering and [2]Faculty of Civil Engineering,
National Institute of Technology, Silchar, India

SUMMARY

Peat is a unique type of soil whose properties vary widely, making it a very poor foundation material for construction purposes. Therefore, before starting any construction on ground that overlies a peat layer, it is essential to understand the properties of the peat. The purpose of this study was to investigate the properties of different peats that occur in Northeast India. Peat samples were collected from four sites located in the states of Assam, Tripura and Manipur. The names of the sites were: National Highway 39 (NH 39), Kalinagar Tea Estate (KTE), Indo-Bangladesh border (IBB) and National Institute of Technology, Manipur (NITM). The upper surfaces of the peat layers studied were 1–2 m below ground level and their average thickness was 3–9 m. Field and laboratory investigations were conducted to determine degree of decomposition, together with physicochemical and engineering properties of the peat. Microstructural and thermal analyses were also carried out. We found that high organic matter content and slight peat decomposition increased water retention capacity and acidity while simultaneously reducing specific gravity and bulk density. Furthermore, high organic matter content reduced strength and increased compressibility. Microstructural and thermal analyses helped to elucidate the morphological, mineralogical and thermal decomposition characteristics of the peats, and these results largely supported the outcomes of the field and laboratory tests. Overall, the engineering properties of peat soils from IBB and NITM were inferior to those of the soils from NH39 and KTE.

KEY WORDS: engineering properties, microstructure, organic matter, physical properties, thermal analysis

INTRODUCTION

All over the world, rapid population growth and urbanisation are creating a need for the development of infrastructure, which ultimately increases the demand for land to a point where it is necessary to utilise even problematic peatland areas (Sing *et al*. 2009). Because peat soil has poor load-bearing capability and highly variable properties, any construction undertaken on peatlands without taking due account of peat properties may lead to disastrous consequences. Therefore, it has become essential to understand the physical, chemical and engineering properties of peat (Rahgozar & Saberian 2015).

Peat is an accumulation of partly decomposed organic matter which usually comprises the remains of peat-forming plants (e.g., mosses and sedges). Degree of decomposition is considered to be one of its crucial properties (Klavins *et al*. 2008). The colour of peat generally varies from light reddish brown (fibrous peat) to black (amorphous peat) and it possesses a light and spongy consistency (Huat *et al*. 2014). It forms because the microbial decay of plant remains is retarded under completely anaerobic acidic conditions (Bell & Culshaw 2001, Rahgozar & Saberian 2015).

Peat covers nearly 3 % of the earth's land surface (Gorham 1991) and around 60 % of the world's wetlands are peat-forming (Huat *et al*. 2011). After North America, Asia is the second most peat-dominated continent, hosting around 28 % of the global peatland area (Lappalainen 1996). In Asia peat has its province in Japan, Malaysia, Bangladesh, China and India (Paul *et al*. 2018). However, only limited information is available regarding the distribution of peatlands in India. According to the Indian Council of Agricultural Research (ICAR), approximately 88.756 km^2 (i.e. 2.17 %) of India is covered by peat soils. Thomas *et al*. (1974) reported 47 areas with peat deposits in Nilgiri region in the southern part of Tamil Nadu state, while Mascarenhas (1997) noted widespread occurrence of peat on the Western Continental Shelf of India. Narayana *et al.* (2002) mentioned the presence of peat deposits around Vembanad Lake in the southern state of Kerala. Peat soils reach a distributional limit in the eastern part of the country. Das (2009) described the geobotanical composition of peat samples collected from Garia in the southern part of Kolkata region (West Bengal state). Reddy *et al.* (2014) subsequently found peats with highly variable organic matter content (15–30 %) in Kolkata region.

However, no studies have been carried out on peatlands in the north-eastern part of India.

For construction engineers, the most crucial problems associated with peat are extremely high water storage capacity, low bulk density, high acidity, high void ratio, very low shear strength and high compressibility. Other complications that generally arise when dealing with this soil type are difficulties in sampling, stabilisation, solidity, in situ testing and construction (Huat *et al*. 2014). These atypical characteristics of peat make it unique amongst soil materials, and limit the possibilities for habitation and the construction of roadways or any other infrastructural development on or through it.

The primary objective of this study is to provide information about the physicochemical, engineering and microstructural properties of peats occurring in Northeast India, with a view to improving our ability to ensure that homes and other constructions can be supported safely in peatland areas. A proper characterisation of these peats is also crucial for agronomy, which is an important and developing economic activity in this region.

METHODS

Study sites

In this study, four different peat-dominated areas in three different states of Northeast India (Assam, Tripura and Manipur) were investigated. Typical problems associated with each of the investigated locations are highlighted in Figure 1. The climate of India ranges from tropical in the south to temperate in the north-east, where mean annual air temperature and relative humidity lie in the ranges 5–30 °C and 70–85 %, respectively (Jhajharia *et al.* 2009). Parthasarathy *et al.* (1995) found that mean annual precipitation (MAP) in Northeast India ranges from 1577 to 6002 mm, due to the ‘orographic barrier’ effect of high mountains in this region (Mahanta *et al.* 2012); and the prevalence of high-intensity rainfall combined with dense forest vegetation and low decomposition rate promotes the accumulation of soil organic matter (Sarkar 1994). Moreover, these authors report that the soils at higher altitudes are strongly acidic because the high precipitation causes leaching of the bases from ion-exchange complexes.

Figure 1. (A) and (B): embankment subsidence followed by heaving and shrinkage of adjacent ground at National Highway 39 (NH39); (C): a tilting building on peat at Kalinagar Tea Estate (KTE); (D): an existing structure sinking into the soil near the campus of National Institute of Technology, Manipur (NITM).

Peat was collected from two sampling sites in Assam, one in Tripura and one in Manipur (Figure 2, Table 1). Brief information about the sampling sites is given below:

- NH39 (National Highway 39) is located within a wetland in the Cachar district of Assam. The MAP of Cachar is 3144 mm, which leads to large water storage in that region. The water table is usually almost at ground level. The uppermost sediment is a two-metre thick layer of clay, and this overlies a four-metre thick layer of organic material. Below the organic material there is another two-metre thick layer of clay and sand.
- KTE (Kalinagar Tea Estate) is located in the Hailakandi district of Assam, in somewhat undulating terrain with a wide vista of tea plant cultivation. Most of the landscape consists of elevated (dome-shaped) landforms and shallow basins. The ground is strewn with tea leaves, banana tree branches and various large fallen parts of other trees. The MAP of Hailakandi district is 3075 mm. Peat is present from 1.4 to 5.8 m below ground level (b.g.l.); i.e., the peat layer is 4.4 m thick. The peat is overlain by a layer of blackish organic clay and underlain by silty material.
- The IBB (Indo-Bangladesh border) is located at Agartala, within the extensive wetland area that dominates the western part of Tripura state. The MAP of Tripura is rather high (2100 mm), leading to the occurrence of large water bodies in that region. Moreover, this troublesome area of peatland is an international corridor connecting the two nations of India and Bangladesh. The sampling site is totally submerged, and the peat layer (underlain by sand) extends from 1 to 10 metres b.g.l.
- NITM (National Institute of Technology, Manipur) is in Manipur state. Almost 92 % of Manipur consists of hilly terrain with high MAP (1482 mm), leading to a great accumulation of organic matter in lowland soils. The soil samples were collected on the NITM campus, which is surrounded by mountain slopes as well as by marshy land. At NITM, the uppermost 0.5 m of the soil profile consists of organic clay, then there is a 3 m thick peat layer underlain by blackish clay.

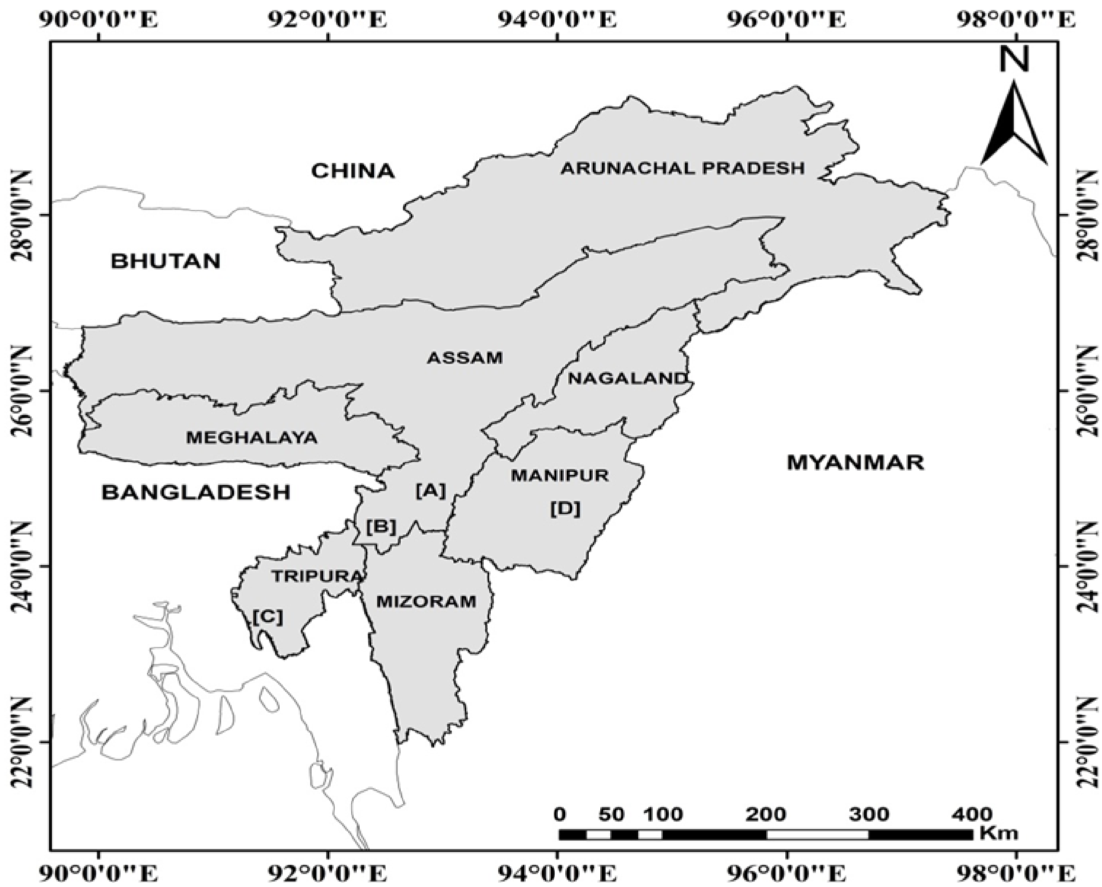

Figure 2. The locations of the four sampling sites within the states of Northeast India: (A) = NH39; (B) = KTE; (C) = IBB; (D) = NITM).

Sample collection

The peat samples were collected from soil pits dug manually until the upper peat horizon was reached. Before sampling, the degree of peat decomposition was determined using the von Post scale (von Post 1922). The undisturbed samples for unconfined compressive strength (UCS), density and hydraulic conductivity measurements were sampled from the upper peat horizons using a shelby tube (38 mm × 210 mm), a core cutter (100 mm ×130 mm) and the standard permeameter mould (100 mm × 130 mm). A thin layer of grease was applied smoothly to the inner surfaces of the samplers/tubes/rings to reduce side friction. To obtain samples for the oedometer test (Landva *et al*. 1983, Reddy *et al*. 2014), a block of undisturbed peat was extracted from the soil pit and samples were obtained by carefully pushing a standard consolidation ring (60 mm × 20 mm) into the block. After collection, the undisturbed samples were sealed with paraffin wax (to prevent moisture loss) before transfer to the laboratory. Disturbed samples were also collected using a hand auger, for determination of the following soil properties: specific gravity, natural moisture content, Atterberg limit, organic matter content, ash content, fibre content, soil pH, electric conductivity and peat compaction.

Physicochemical properties

The natural soil moisture content was determined by drying a sample of peat in an oven for 24 hours at a temperature of 105 °C as per IS 2720 Part 2 (1973). Bulk density (i.e., in-situ density) was determined by the core cutter method as per IS 2720 Part 29 (1975). Specific gravity was measured using a density bottle method based on the procedure of IS 2720 Part 3 (1980). Soil pH was determined using a digital pH meter (Model LI 120) and electric conductivity using a conductivity meter (Model CM 180), according to ASTM D2976 (2015). The Atterberg limits test was performed as per IS 2720 Part 5 (1985). Liquid limit was determined on both oven-dry and undried soil samples using Casagrande's apparatus. Plastic limit was determined by rolling out a thread of the fine portion of the soil on a non-porous glass plate until it began to crumble at a diameter of approximately 3 mm. The shrinkage limit of the peat soil was measured by the mercury displacement method as per IS 2720 Part 6 (1972). The loss on ignition test was performed to determine organic matter and ash contents as per ASTM D2974 (2014). Fibre content was determined from the dry weight of fibre retained on a 0.15 mm sieve as per ASTM D1997 (2013). All values reported here are means calculated from three replicates.

Engineering properties

The standard Proctor test was conducted to determine the maximum dry density (MDD) and optimum moisture content (OMC) of the peat as per IS-2720 Part 7 (1980). The UCS test was carried out on undisturbed peat samples as per IS 2720 Part 10 (1991). The shear strength parameters were determined by the unconsolidated undrained (UU) triaxial test at four different cell pressures (50, 100, 150 and 200 kPa) as per IS 2720 Part 11 (1993). The UCS and UU test results are reported as averages of three trials. The consolidation parameters were determined on undisturbed samples using an odometer cell as per IS 2720 Part 15 (1965). Compression index (c_c) values were calculated from the void ratio (e) - effective stress (σ'_v) (e - logσ'_v)

Table 1. General characteristics of the study sites. m a.s.l = metres above sea level; m b.g.l = metres below ground level.

State	Site name	Coordinates	Altitude (m a.s.l.)	Water table level (m b.g.l.)	Peat thickness (m)
Assam	NH39 (A)	24° 49' 38.40" N 92° 47' 52.30" E	22	0.5	2.0–6.0
Assam	KTE (B)	24° 41' 4.88" N 92° 33' 51.62" E	21	1.4	1.4–4.4
Tripura	IBB (C)	23° 49' 45.55" N 91° 16' 40.24" E	71	+0.1	1.0–10
Manipur	NITM (D)	24° 48' 50.28" N 93° 57' 1.04" E	786	0.5	0.5–3.5

curve. The pre-consolidation pressure (σ'_p) was calculated from the same e - logσ'_v curve using the graphical method proposed by Casagrande (1936). The coefficients of compressibility (a_v) and volume compressibility (m_v) were calculated from the void ratio (e) - effective stress (σ'_v) (e - σ'_v) curve at high stress (400–800 kPa). The coefficient of consolidation (c_v) was calculated from the time-settlement curve plotted on a logarithmic scale. On the other hand, the coefficient of secondary compression (c_α) was determined from the slope of the void ratio versus logarithm of time (e - $\log_{10}$t) curve for a period of 4–24 hours at a high stress level (800 kPa). Finally, the falling head permeability test was carried out as per IS 2720 Part 17 (1986).

Microstructural characterisation

The morphology of the peats was studied using field emission scanning electron micrography (FESEM) followed by Energy Dispersive X-ray Spectroscopy (EDX or EDS). A very fine portion (0.05–0.08 g) of dried peat was mounted on a copper holder then coated with a thin layer of gold. The coated sample was placed in a Carl Zeiss FESEM (Model - ΣIGMA) operating at 5 kV to reveal the micro-structural orientation. The mineralogical composition of the soil was investigated by X-ray diffraction (XRD). To identify the crystalline phases present, a soil sample finer than 75 µm was placed on an X-ray diffractometer (Rigaku TTRAX, Seifert XRD 3003 T/T) with CuKα (λ = 1.5418 Å) as source radiation, input voltage 40 kV and current 30 mA. The thermal behaviour of the soils was studied by thermal gravimetric analysis (TGA) and derivative thermogravimetry (DTG) using a thermal analyser (Netzsch STA449F3A00). This analysis was carried out with a heating rate of 10 °C min^{-1} in a nitrogen atmosphere and a purging rate of 100 ml min^{-1}. The maximum temperature reached during the analysis was 800 °C.

RESULTS

Physicochemical properties

The colour of the studied peats ranges from brownish (KTE) through dark brown (IBB, NITM) to black (NH39, IBB, NITM). NH39 (8 % fibre) is strongly decomposed (H8–H10), and is thus classified as ‘sapric’ peat. KTE (77 % fibre) is slightly decomposed (H1–H4) ‘fibric’ peat whereas, in contrast, IBB and NITM are moderately decomposed (H5–H7) ‘hemic’ peats. Due to their high ash contents (≥ 15 %), all of the studied soils are classified as ‘high ash’ peats according to ASTM D2974 (2014). NH39 and KTE are moderately acidic with pH values of 5.1 and 5.5, respectively; whereas IBB is slightly acidic (pH 6.4) and NITM is highly acidic (pH 4.5) (Table 2). NH39 and KTE contain lower amounts of organic matter than IBB and NITM, whereas specific gravity is higher for NH39 (2.0) and KTE (1.9) than for IBB (1.4) and NITM (1.5; Table 2), suggesting an inverse relationship between organic matter content and specific gravity. Water content lies in the range 268–600 % and shows

Table 2. Physicochemical properties of Northeast Indian peats (n = 3), adapted from Paul *et al*. (2018). SD = standard deviation.

Soil properties	**NH39**		**KTE**		**IBB**		**NITM**	
	mean	**SD**	**mean**	**SD**	**mean**	**SD**	**mean**	**SD**
Organic matter content (%)	20.0	0.91	36.0	1.19	66.0	1.73	76.0	1.44
Ash content (%)	80.0	-	64.0	-	34.0	-	24.0	-
Fibre content (%)	8.00	1.47	77.0	0.63	37.0	1.53	450	2.64
pH	5.1	0.05	5.5	0.08	6.4	0.06	4.5	0.05
Electric conductivity (µS cm^{-1})	199	2.08	204	3.21	83.0	2.51	333	3.51
Specific gravity, G_s	2.00	0.05	1.90	0.08	1.40	0.05	1.50	0.05
Water content (%)	268	12.1	600	18.4	590	13.5	404	12.6
Bulk density (g cm^{-3})	1.17	0.03	1.01	0.09	1.11	0.08	1.14	0.07
Peat material type (ASTM D 1997)	Sapric	-	Fibric	-	Hemic	-	Hemic	-
Degree of decomposition (von Post 1922)	H8–H10	-	H1–H4	-	H5–H7	-	H5–H7	-

a decreasing trend with increasing degree of decomposition. NH39 (strongly decomposed) has lower water content than KTE (slightly decomposed), IBB and NITM (both moderately decomposed). Bulk density is in the range 1.01–1.17 g cm^{-3} and is higher for the sapric peat (NH 39) than for the fibrous (KTE) and hemic (IBB, NITM) peats. The range of electric conductivity is 83–333 μS cm^{-1}. Atterberg's limit values are lower for the less-organic peats (NH39, KTE) than for the highly organic peats (IBB, NITM) (Table 3). The ranges of liquid limit and plastic limit are 68–97 % and 56–66 %, respectively. Shrinkage limit is in the range 33–44 % and increases with organic matter content.

Engineering properties

MDD decreases and OMC increases with increase in organic matter content (Figure 3). There is a gradual flattening of the compaction curve as organic matter content increases. MDD and OMC vary across wide ranges (0.65–1.14 g cm^{-3} and 41.8–78.2 %, respectively). UCS is very low, ranging from 8 to 11 kPa (Table 4), and the failure envelopes are almost-parallel straight lines that do not change significantly with organic content (Figure 4). The frictional angle ranges from 2.5 to 3.1°, whereas the cohesion values range from 5.8 to 13.9 kPa and decrease as organic matter content increases (Table 4).

The highly organic IBB and NITM peats undergo a sharp volumetric decrement with increasing effective stress, finally yielding compression index (c_c) values of 3.72 and 3.49, respectively (Figure 5, Table 5). The NH39 and KTE peats undergo more gradual volumetric changes with increasing effective stress, thus rendering low c_c values (1.43 and 2.99, respectively). The pre-consolidation pressures (σ'_p) calculated for peats with high organic matter content are higher than those calculated for peats with lower organic matter content. The IBB and NITM peats have σ'_p values of 56 and 63 kPa, respectively; whereas, NH39 and KTE have σ'_p values of 78 and 72 kPa, respectively. The range of values for

Table 3. Atterberg limits of Northeast-Indian peats; data from Paul *et al*. (2018). n.d. = not determined.

Atterberg limits	**Value**			
	NH39	**KTE**	**IBB**	**NITM**
Liquid limit, %	68	68	97	72
Plastic limit, %	56	60	n.d.	66
Plasticity index, %	12	8.6	n.d.	6.0
Shrinkage limit, %	37	33	n.d.	44

Table 4. Strength parameters of Northeast Indian peats. UCS: unconfined compressive strength; *c*: cohesion; *φ*: friction angle.

Strength parameters	**Value**			
	NH39	**KTE**	**IBB**	**NITM**
UCS (kPa)	11	10	9	8
c (kPa)	13.9	9.2	6.5	5.8
φ (degrees)	2.5	2.9	2.8	3.1

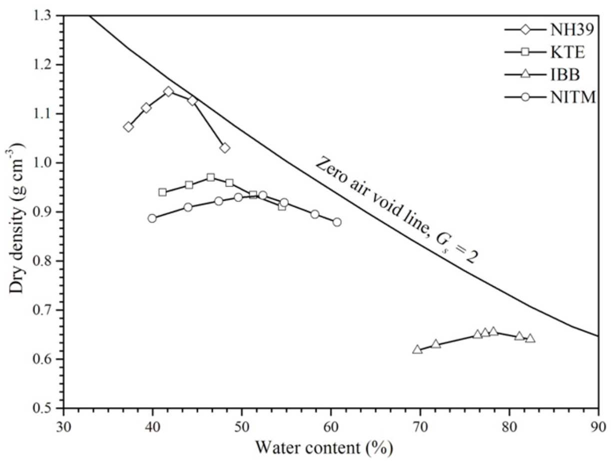

Figure 3. Water content - dry density relationship for Northeast Indian peats.

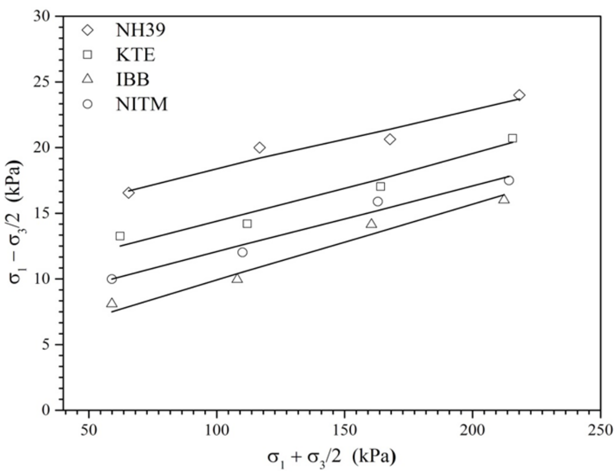

Figure 4. Modified failure envelopes for Northeast Indian peats.

coefficient of compressibility (a_v) is 10.9–28.4 ×10^{-4} m^2 kN^{-1}, and for coefficient of volume compressibility (m_v) it is 4.8–10×10^{-4} m^2 kN^{-1}.

In order to build a comprehensive understanding of the compression pattern of peat, a high range of loading conditions was adopted (i.e. 800 kPa). The change in slope of the time-settlement curve, which indicates the end-of-primary (EOP) consolidation and the transition to secondary compression, is very distinct (Figure 6). The coefficients of consolidation (c_v) determined from Figure 6 decrease with increasing soil organic matter content and the range of values obtained is (1.5–7.8)×10^{-9} m^2 sec^{-1}. It is also noted that the degree of secondary compression (range 0.022–0.069) increases with increasing organic matter content (Table 5). The range in values of compression ratio ($c_c/1+e_o$; where e_0 = initial void ratio) is 0.377–0.465; which means that the 'high compressibility' threshold value of 0.2 is exceeded in all cases. The ratio of c_α /c_c ranges from 0.015 to 0.020 (Table 5). The range of hydraulic conductivity values is 4–4.6 ×10^{-6} cm sec^{-1} (Table 5), and these values show an almost negligible symmetrical decreasing trend in order of degree of decomposition and porosity. KTE peat is slightly more permeable than the other peats studied.

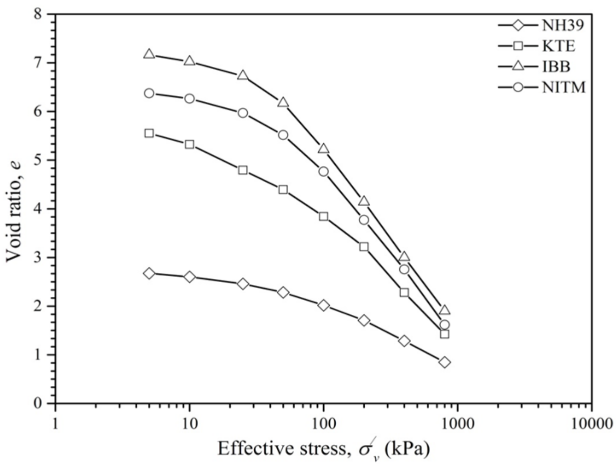

Figure 5. Void ratio - effective stress (e-log$_{10}$σ'$_v$) relationship for Northeast Indian peats.

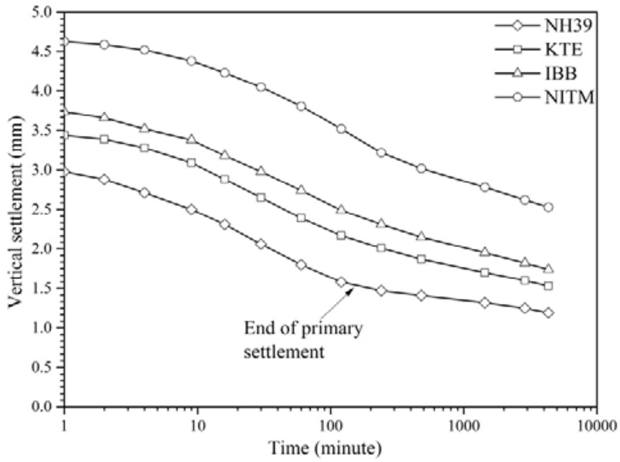

Figure 6. Time-settlement curves for Northeast Indian peats.

Table 5. Consolidation parameters of Northeast Indian peats. Note that a_v and m_v are calculated at stress level 400–800 kPa and c_v, c_α, and k at 800 kPa.

Consolidation parameters	**Value**			
	NH39	**KTE**	**IBB**	**NITM**
Compression index, c_c	1.43	2.99	3.72	3.49
Pre-consolidation pressure, σ'_p (kPa)	78	72	56	63
Coefficient of compressibility, a_v (m^2 kN^{-1})	10.9×10^{-4}	21.4×10^{-4}	28.3×10^{-4}	28.4×10^{-4}
Coefficient of volume compressibility, m_v (m^2 kN^{-1})	4.8×10^{-4}	6.5×10^{-4}	10×10^{-4}	7.6×10^{-4}
Coefficient of consolidation, c_v (m^2 sec^{-1})	7.8×10^{-9}	4×10^{-9}	1.5×10^{-9}	3.6×10^{-9}
Secondary compression index, c_α	0.022	0.049	0.067	0.069
Ratio of compressibility, c_α /c_c	0.015	0.016	0.018	0.020
Compression ratio, $c_c/1+e_0$	0.377	0.439	0.455	0.465
Hydraulic conductivity, k (cm sec^{-1})	4×10^{-6}	4.6×10^{-6}	4.2×10^{-6}	4.3×10^{-6}

Microstructural analysis

The microstructural analysis of NH39 peat reveals a completely amorphous and granular structure with no evidence of plant remains or voids (Figure 7a). On the other hand, KTE peat has a fibrous, distinctly platy and porous structure (Figure 7b). The slightly decomposed nature of KTE peat is confirmed by its high fibre content (Table 2). The presence of platy and porous material is also an indication that this soil has high compressibility and low shear strength (Tables 4 and 5). Moreover, the loosely packed fibres and the randomly scattered identifiable coarse organic remains are quite distinctive. The micrograph of IBB peat shows a predominance of large cavities and voids which are clearly visible as dark spaces in the peat mass; in other words, this peat has a porous structure (Figure 7c). The presence of fibrous material in the micrograph of NITM peat conveys its unsatisfactory nature in terms of load-bearing capacity (Figure 7d).

The results of the EDX analysis show that carbon (C) and oxygen (O) are the predominant elements in the peats, accounting for 71.9 % (NH39), 85.7 % (KTE), 82.1 % (IBB) and 88.2 % (NITM) of total peat mass (Table 6). Among the other elements we noted the presence of silicon (Si) and aluminum (Al), which account for 11–25 % of total mass. The occurrence of Si and O suggests the presence of quartz; while Al, K and Ca may indicate feldspar inclusions in the peat; and the presence of C along with Ca and O might reflect an occurrence of calcite. Confirmed by the XRD tests, this analysis shows that the main minerals present in all of the peats we studied are calcite, quartz, hydrated halloysite, feldspar and clay, of which the most abundant is quartz (Figure 8).

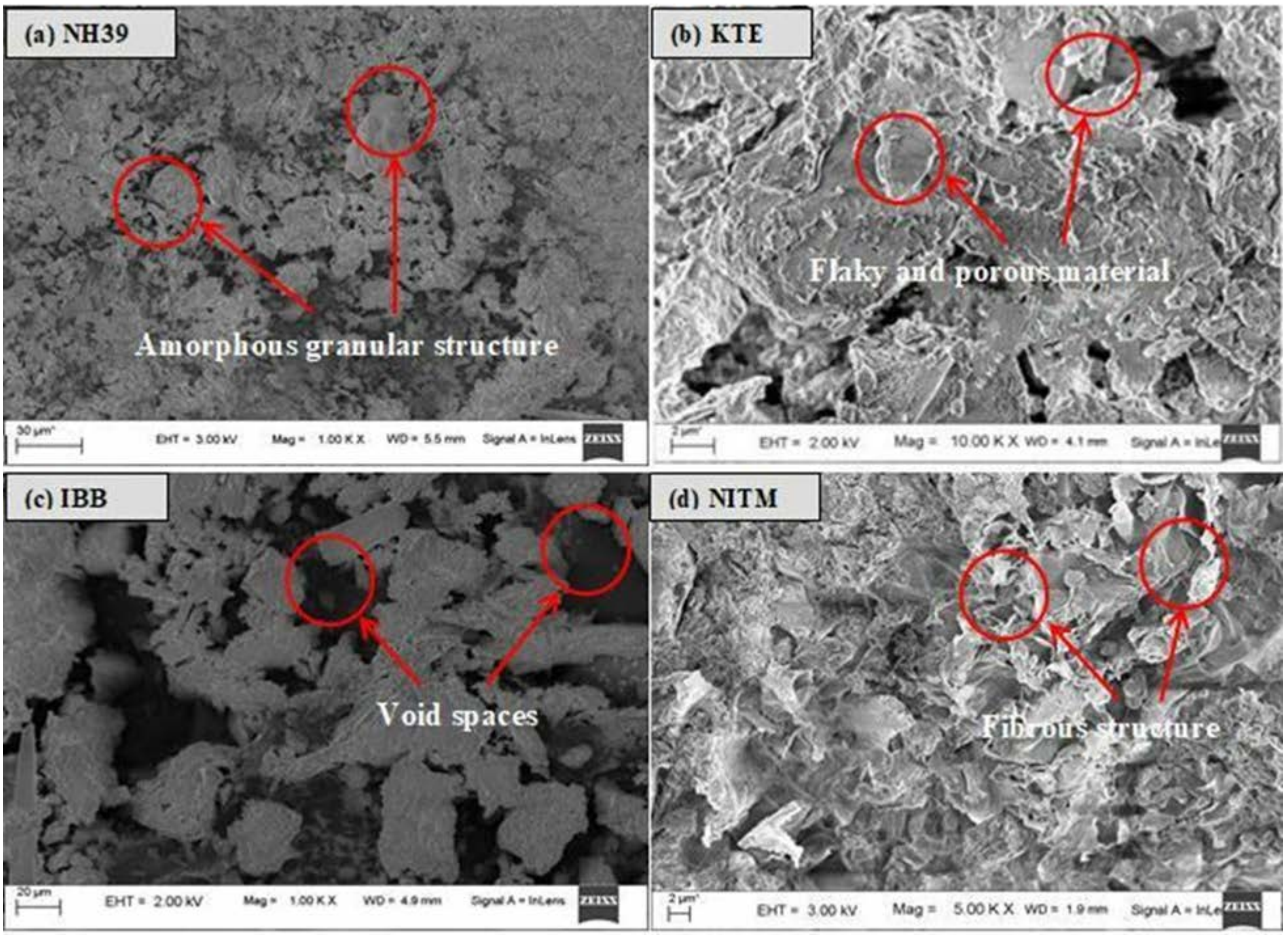

Figure 7. FESEM analysis of Northeast Indian peats.

Table 6. Elemental composition (% weight) of Northeast Indian peats. <d.l. = below detection limit.

Element	NH39	KTE	IBB	NITM
O (%)	49.9	42.6	38.5	43.3
C (%)	22.0	43.1	43.6	44.9
Si (%)	18.2	8.10	7.37	6.27
Al (%)	6.57	4.60	7.39	5.07
Fe (%)	1.21	0.85	1.79	0.60
K (%)	1.23	0.35	0.57	0.70
Mg (%)	0.38	0.15	0.46	0.35
Ti (%)	<d.l.	0.10	0.20	<d.l.
Ca (%)	<d.l.	0.15	0.19	0.25
S (%)	<d.l.	0.10	<d.l.	<d.l.

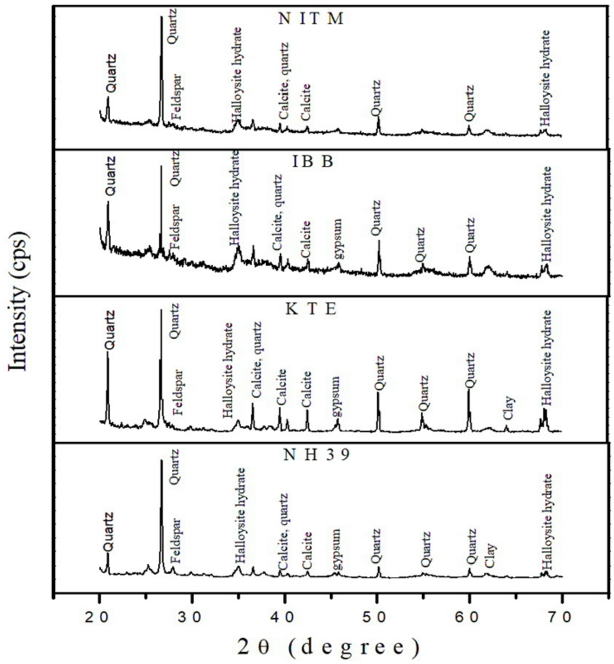

Figure 8. XRD analysis of Northeast Indian peats.

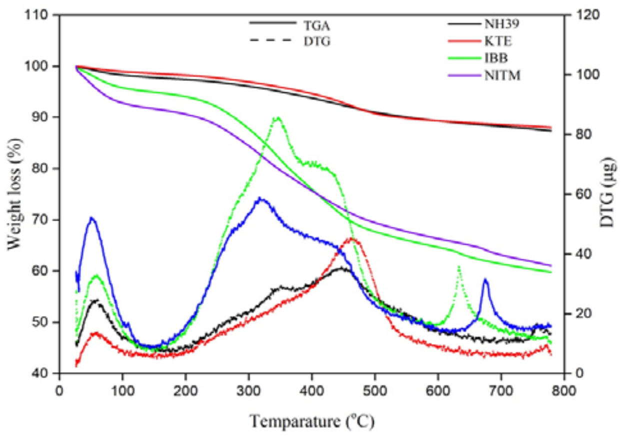

Figure 9. Thermal analysis of Northeast Indian peats.

The TGA analysis provided information on the percentage mass loss by thermal decomposition of peat (see e.g. Misnikov 2016) occurring in the three temperature ranges 27–150 °C, 150–600 °C and beyond 600 °C. In the first stage (involving evaporation of hygroscopic water at 27–150 °C), the mass loss was 0.95–4.25 %. In the second stage (150–600 °C) the mass loss was 2.99–17.06 %; and in the third stage (beyond 600 °C) it was 0.09–3.38 %. It is quite clear from the TGA curve (Figure 9) that the IBB and NITM peats lost more mass than the NH39 and KTE peats in all three stages. The DTG curve shows that, in the second and third stages, there was a slight temperature delay in reaching the commencement of breakdown when the organic matter content of the soil was reduced.

DISCUSSION

Physicochemical properties

The Northeast Indian peats described here are characterised by a wide range of values for degree of decomposition, which reflects the presence of all three types of peat (fibric, hemic and sapric). The pH values we recorded conform well with the ranges (4.6–6.8) reported for Malaysian peats by Deboucha & Hashim (2009) and Kalantari & Huat (2009). The inverse relationship we observed between organic matter content and specific gravity agrees well with results published for Malaysian peat by Duraisamy *et al.* (2009) and for Iranian peat by Badv & Sayadian (2012). Moreover, Ulusay *et al.* (2010) and Badv & Sayadian (2012) report specific gravity values from Turkey and Iran (1.6–2.3) that are similar to ours. In general, peats have a wide range of natural soil water contents, from 77 % to 850 % (Deboucha *et al.* 2008, Rahman *et al.* 2015). This an effect of the large pore spaces and the presence of perforated plant structures (Huat *et al.* 2014). Furthermore, due to its high organic matter content, peat possesses high cation exchange capacity (Huang *et al.* 2009). The water content of Northeast Indian peats varies within the range 268–600 %, as also reported for peat soils in Malaysia by Deboucha *et al.* (2008) and Rahman *et al.* (2015). The range of bulk density observed here (1.01–1.17 g cm^{-3}) was similar to the ranges found by Duraisamy *et al.* (2007) and Deboucha & Hashim (2009) (0.81 to 1.60 g cm^{-3}).

The wide range of electrical conductivity recorded amongst the studied soils (83–333 µS cm^{-1}) is similar to that reported for soils with high water content by Asadi & Huat (2009). The electrical conductivity of soil is related to the mobility of electrical charges in water and invariably depends on the soil water retention capacity (Pozdnyakov *et al*. 1996). However, apart from water content, factors such as colloids (clay/humus), the presence of ions, porosity and temperature significantly affect the electrical conductivity (Huat *et al*. 2014).

Atterberg's limits play a significant role in the classification/characterisation of fine-grained soils, but are considered to be less effective in the case of peat soils (Jarrett 1982, Ulusay *et al*. 2010, O'Kelly 2015). Rahman *et al*. (2015) noted the non-availability of a plastic limit value for most peat soils. Malkawi *et al*. (1999) and Huang *et al*. (2009) mentioned that the Atterberg limits of peat soils are governed by two opposing principles; the high moisture holding capacity of organic substances tends to increase the limits while aggregation induced by organic matter tends to reduce them. However, several studies have reported that liquid and plastic limit values increase with increasing organic matter content (Odell *et al*. 1960, Abdallah *et al.* 1999). The liquid limit range of Northeast Indian peats (Table 3) showed good similarity to that for Malaysian tropical peats (69–95 %) as reported by Kolay *et al*. (2011); and their shrinkage limit values were in good agreement with Huang *et al.* (2009) who quite clearly demonstrated an increase in shrinkage limit with an increase in organic matter content. Huat (2004) mentioned that the shrinkage limit test for soil is less useful for civil engineering purposes and this is why there are very few literature sources of shrinkage limit values for peat soils.

Engineering properties

The compaction behaviour of soil plays a crucial role in the construction of roads, railway embankments, landfills, earth dams and other aspects of civil engineering (Ranjan & Rao 2000). The increase of OMC with increasing organic matter content can be attributed to the fact that the large void spaces in organic matter enable it to hold more water and this eventually increases the OMC value. The reduction of MDD with increasing organic matter content can be explained in terms of increased organic matter lowering particle density, thus making the soil less dense and finally reducing the MDD. Our compaction results (OMC and MDD) were similar to the ranges reported by Asadi *et al*. (2011), Kolay & Rahaman (2016) and Venuja *et al*. (2017).

Our very low UCS values might be explained by the presence of a high amount of organic matter, as indicated in other studies (e.g., Huang *et al*. 2009, Rabbee & Rafizul 2012, Rahgozar & Saberian 2015). Furthermore, Malkawi *et al*. (1999) reported increasing peat strength at an advanced stage of peat decomposition. This is due to diminishing soil pore space causing increased peat density. The observed UCS range (8–11 kPa) of Northeast Indian peats showed good similarity with results reported by Duraisamy *et al*. (2007) and Rahgozar & Saberian (2015) (Table 4). The observed shear strength parameters (c and φ) of Northeast Indian peats (Table 4) were similar to the results of Al-Raziqi *et al.* (2003), where c and φ (from direct shear box tests on Malaysian peats) varied within the ranges 6–17 kPa and 3–25°, respectively.

The high compression index (c_c) values of the studied peats are similar to results published by Leonards & Girault (1961) and Huat *et al*. (2014) who reported ranges of 2–5 and 2–15, respectively. In general, the pre-consolidation pressure (σ'_p) is the maximum effective pressure that a soil can reach. It is of great importance because it divides the deformation pattern into elastic and inelastic regions and indicates the starting point of the higher settlement zone (Yang *et al*. 2014). The dominance of water in the IBB and NITM peats would have reduced the effect of any loading pressure applied in the past, resulting in a lower σ'_p value. On the other hand, the NH39 and KTE peats are surrounded by nearby habitations and subject to moderate traffic movement, which would eventually increase the σ'_p value. The observed σ'_p range (56–78 kPa) of Northeast Indian peats was slightly higher than the ranges mentioned by Johari *et al.* (2016). The high range of coefficient of compressibility (a_v) and coefficient of volume compressibility (m_v) values for soil with high organic matter content has also been reported by Adejumo (2012) and Develioglu & Pulat (2017), respectively, whereas Farrell *et al*. (1993) reported a similar range of consolidation coefficients (c_v) and mentioned that a decrement in coefficient of consolidation is more typical for highly organic soils. The range of secondary compression index (c_α) in the studied peat soils was similar to ranges reported by other researchers (e.g., Duraisamy *et al*. 2007, Kaniraj *et al*. 2011, Dehghanbanadaki *et al*. 2016). However, the IBB and NITM peats, with c_α exceeding 0.064, fall into the category of highly secondary compressible soils (Mesri 1973). The compression ratio ($c_c/1+e_o$) and c_α/c_c values were quite similar to results reported by Duraisamy *et al*. (2007). According to O'Loughlin & Lehane (2003), any soil having a $c_c/1+e_o$ value exceeding 0.2 lies in the very compressible zone.

Our hydraulic conductivity results were quite similar to those published by Huat *et al*. (2014). However, it has been observed that the permeability values measured in falling head tests deviate greatly from results back-calculated from the consolidation test. A similar type of discrepancy was noticed by Kaniraj & Gayathri (2004) during a study on the permeability and consolidation characteristics of compacted fly ash. These authors suggested that the deviations may be due to errors in the calculation of c_v by conventional methods, and they finally preferred the use of directly measured permeability values over derivation from consolidation results.

Microstructural analysis

The presence of a dispersed discontinuous network of large voids was clearly visible, along with randomly scattered fibres. The morphology of Northeast Indian peats revealed good conformity with the findings of Latifi *et al.* (2016). The IBB and NITM peats seemed to be at the stage of moderate decomposition. It was also clear from the micrographs that the occurrence of voids decreased with the advancement of peat decomposition. This inference is in good agreement with the results of Rahgozar & Saberian (2015). The elemental composition of the studied peats was similar to results published by Lucas (1982), Andriesse (1988) and Rahgozar & Saberian (2015). The mineral presence in Northeast Indian peats (Figure 8) is similar to that reported for peats in other regions (e.g., Twardowska & Kyziol 1996, Eriktius *et al*. 2001, Kwong *et al*. 2001, Girardello *et al*. 2012, Salam 2017). Leong & Eriktius (2013) and Moayedi *et al*. (2014) reported kaolinite as the main mineral component of the clay fraction in peat.

The analysis of pyrolytic decomposition revealed that mass loss occurs in all three temperature ranges (Figure 9). In the first range, from room temperature to around 150 °C, mass loss can be attributed to the loss of hygroscopic water (Almendros *et al*. 1982, Zhao *et al*. 2014). In general, water occurs in wood-based materials like peat (1) as capillary water and (2) as hygroscopic water (Moghtaderi 2006). Oven drying removes only the capillary water, while the hygroscopic water is removed during the process of thermo gravimetric analysis (Moghtaderi 2006). The loss of mass in the temperature range 150–600 °C resulted from the breakdown of cellulose, polysaccharides, external functional groups of humic substances and aliphatic compounds (Francioso *et al*. 2003); whereas the mass loss in the third temperature range (above 600 °C) arose from thermal decomposition of aromatic constituents of lignin and other humic material (Rustschev & Atanasov 1983, Bergner & Albano 1993). Overall, the TGA results for Northeast Indian peats showed that the maximum percentage decomposition occurred in the temperature range 150–600 °C.

A comparison of our results with information from previously available literature (Table 7) shows that Northeast Indian peats are very similar to the peats of Turkey and Iran in terms of organic matter content, natural moisture content and bulk density, while they resemble Malaysian peats in terms of pH

Table 7. Comparison of the properties of Northeast Indian peats with information available from published literature. Data for Turkey are taken from Ulusay *et al.* (2011); for Iran from Badv & Sayadian (2011); for Malaysia from Duraisamy *et al*. (2007), Wong *et al*. (2008), Kalantari & Huat (2009) and Kolay *et al*. (2011); and for other parts of India from Thomas *et al.* (1974) and Reddy *et al.* (2014). n.a. = not available.

Soil property	Northeast India	Malaysia	Turkey	Iran	Other parts of India
Degree of decomposition	H1–H10	H1–H4	H5–H7	H5–H7	n.a.
Organic matter content (%)	20.0–76.0	80.2–96.5	22.3–71.7	25.0–77.0	20.1–33.8
Natural water content (%)	268–600	198–668	118–559	100–623	39.1–90.0
Bulk density (g cm^{-3})	1.01–1.17	NA	0.909–1.35	0.97–1.37	1.26–2.02
Liquid limit (%)	68.0–97.0	69–95	148–320	n.a.	60.0–65.0
Specific gravity, G_s	1.4–2.0	1.0–1.7	1.6–2.4	1.6–2.3	2.1–2.2
pH	4.5–6.4	3.5–6.8	n.a.	n.a.	n.a.
Void ratio, e	5.36–11.4	n.a.	2.19–4.69	2.42–11.2	n.a.
Compression index, c_c	1.43–3.72	1.45–3.21	n.a.	n.a.	n.a.

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and Iranian peats in terms of void ratio. The natural moisture content and the compression index of Northeast Indian peats match the published ranges for Malaysian peats very well. While the range of specific gravity is similar to ranges reported from Turkey and Iran, the liquid limit values resemble data from Malaysia. On the other hand, a comparison with peats from other parts of India indicates that the properties of Northeast Indian peats vary more widely than those of peat soils in other parts of the country. A dominating reason for the wide variation of peat properties from place to place may be the fact that each place has its own unique combination of vegetation composition and climatic regime.

This characterisation of Northeast Indian peats provides information for foundation design and other forms of constructional activity in the field of civil engineering that will help minimise adverse effects and prevent post-construction problems. Prior to our study, no such research on peat soils was being conducted in India. Thus, our results provide a significant input to this field of study and we hope they will inspire other investigators to venture into peat research in other unexplored parts of India.

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Author for correspondence: Dr Monowar Hussain, Assistant Professor, Department of Civil Engineering, National Institute of Technology, 788010 Silchar, India.
Tel: +91-9435551673; Email: monowarhussain@gmail.com