Static and dynamic characterisation of Agartala peat

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SUMMARY

Peat is a unique soil type whose properties vary widely compared to other soils due to its high water content, low shear strength and high compressibility. Thus, construction on peat deposits is challenging and needs proper attention from engineers. The present study attempts to characterise the engineering characteristics of peat samples collected from 140 boreholes across Agartala town, in the Northeast Region of India. Field and laboratory investigations were conducted to determine physicochemical, microstructural, mineralogical, resistivity, static and dynamic engineering parameters. Physicochemical and microstructural investigation suggested a hemic classification for the Agartala peat. Further, results show that water content, liquid limit and settlement parameters significantly increase with increased organic matter content. In contrast, a decreasing trend in specific gravity, bulk density and shear strength was observed with increase in organic matter content. Results obtained from the present study showed a similar pattern of changing engineering properties with variation in organic matter content when compared with previous studies across the world. Finally, a geographic information system map of Agartala town was developed, highlighting the spatial variation of different physicochemical characteristics of peat, and site-specific empirical correlations for Agartala peat were presented.

KEY WORDS: Bender element, GIS, India, marshy land, organic matter content

INTRODUCTION

When the decomposition rate of vegetative and animal remains within soil is exceeded by accumulation, this results in peat formation. Waterlogged conditions, for example in slow-flowing rivers or areas under consistently high rainfall may offer ideal ambient environmental condition for peat formation (Xintu 2009, Li *et al.* 2020). Depending on the extent of decomposition of plant and animal matter under anaerobic conditions, different varieties of peat occur. These can be classified using terms such as sapric, hemic and fibric, where sapric is highly decomposed, hemic moderately decomposed and fibric being slightly decomposed (Zulfikley *et al.* 2013, Kolay & Animur 2015, Paul *et al*. 2018, Khanday *et al.* 2021). Peat can be easily distinguished from other soil materials as its colour varies from dark brown to black, indicative of high organic matter (OM) content (Paul & Hussain 2019, Sarkar & Sadrekarimi 2020). Peat has various disadvantages from a construction point of view owing to its high *w*, high Atterberg limits, low shear strength and permeability (Moayedi & Nazir 2018, Trafford & Long 2020). However, it is also a very important part of the peatland ecosystem because it stores huge amounts of carbon, and as such it has a crucial role in climate change mitigation (Joosten 2009, Humpenöder *et al.* 2021). In fact, OM is a vital parameter which helps to characterise organic soil and peat. Previously reported studies have indicated that OM content ≥ 27.5 % can be used as a limiting criterion between organic soil and peat (e.g. Hobbs 1986, Huang *et al.* 2009, Nie *et al.* 2012, Chen *et al*. 2019, Paul & Hussain 2019, Ozcan *et al.* 2020, Khanday *et al.* 2021). Hence, the present study applied the same guideline (OM content ≥ 27.5 %) to distinguish the peat layer, although other authors have set higher limits of > 45 % OM to define peat (Wüst *et al.* 2003).

Peatlands are present across 2.84 % of the globe and cover approximately 4.23 million km^2 (Xu *et al.* 2018) stretching from the northern hemisphere to the southern hemisphere. The northern hemisphere accounts for the majority of peatland worldwide, around 90 %, whereas the southern hemisphere accounts for less than 10 % (Lappalainen 1996). Asia contributes nearly 38.4 % of the total global estimate of peatland with the top four major deposits being present in Asian Russia (9,784,930 km^2), Indonesia (1,811,559 km^2), China (9,326,410 km^2) and Malaysia (328,657 km^2) as stated in Xu *et al.* (2018). Although India might not be among the top countries as far as peatlands are concerned still a substantial portion of nearly 88,800 km^2 (2.1 % of total Indian landmass), as per Indian Council of Agricultural Research (ICAR), is occupied by peat deposits. However, knowledge of peatlands across various parts of India is still obscure (Paul *et al.* 2018, Paul & Hussain 2019). India is densely populated with a rising economy and fast infrastructural growth, creating a need to consider peatland areas for construction. Geotechnical characterisation of peat has now become essential, and the present study seeks to address this research need.

Studies have previously been carried out to determine the characteristics of peat available in India (Narayana 2007, Varghese *et al.* 2019, Paul & Hussain 2019, Khanday *et al.* 2021), and studies on peat soil in north-east India have been undertaken recently. Physical and chemical characteristics of peat collected from three north-east Indian states (Manipur, Tripura, Assam) were compared, and improvement techniques were suggested (Paul *et al.* 2018, Paul & Hussain 2019, Khanday *et al.* 2021). Past studies in north-east India have dealt with a limited number of samples from a particular site, with limited examination of spatial variation.

Previous research has also highlighted that peat deposits tend to amplify seismic waves in the event of an earthquake (Wehling *et al.* 2003, Mesri & Ajlouni 2007, Chen *et al*. 2019, Zwanenburg *et al.* 2020). Thus, the response of peat due to seismic waves also deserves special mention as the study area lies in seismic zone-V, as per IS 1893 Part1 (2016). From this point of view, the aim of the study was to investigate the physical, mineral, microstructural, static and dynamic parameters of peat samples collected from Agartala town, and the spatial variation in peat physical characteristics across Agartala is developed using geographic information system (GIS) maps. Empirical correlation equations highlighting relationships between different parameters of Agartala peat are also proposed in this study.

METHODS

Study area

Agartala town is located on flat terrain, with two rivers Haora and Katakhal, as shown in Figure 1. The study area is likewise a flattened bowl shape and the central part is located at the bottom-most part of the bowl, whereas the outer zone in the northern and southern part exhibits more elevated areas. The climate in the study region is subtropical, and varies from moderate to humid; it can be considered to be a borderline tropical monsoon climate with long and hot summers from March to October, with a mean annual air temperature of 25 °C as per Indian Meteorological Department (IMD), which tends to fluctuate with rainfall. A severe south-west monsoon takes place from April to July resulting in flooded rivers, and the mean annual rainfall ranges from 1922 to 2855 mm, according to the IMD. Climate plays a crucial role in peat formation (Gorham 1991, Xintu 2009) and regions with high precipitation, such as Agartala town, are highly favourable for peat formation.

The central part of the town comprises mainly alluvial sediments of loose sands and clayey soils formed in Surma basin during Tertiary age (Sil & Sitharam 2014). Peatlands are thought to be early Holocene in age (Sarangi *et al.* 1990), but this is yet to be confirmed through radiometric dating.

The study area falls within seismic zone V, as per IS 1893 Part 1 (2016) and is highly vulnerable to earthquakes, lying in the Tripura fold belt zone, which is in the proximity of the Bengal Basin and Indo-Burmese arcs in the west and eastern side respectively. The Tripura fold zone has witnessed several moderate to damaging earthquakes in the past (Sil & Sitharam 2014).

Fieldwork and sampling

A total of 140 borehole locations distributed throughout Agartala town (Figure 2) were selected for the present study. The selection of boreholes was attempted keeping an approximate distance of 750 m between boreholes in order to try and represent the spatial variation of subsoil conditions of Agartala town. Exploration depth was kept to a maximum of 25 m below the existing ground level.

Standard penetration test

Standard penetration test (SPT) was conducted as per IS 2131 (1981) by advancing borehole following Auger and wash method. The recorded SPT were corrected following IS 2131 (1981), represented as N_{60} (where N represent number of hammer blows).

Sample collection

Peat samples were extracted both in undisturbed (UDS) and disturbed (DS) states during the SPT test by samplers as outlined in IS 11594 (1985). UDS samples were collected from a depth of 1.5 to 6.0 m using Shelby tubes (0.10 × 0.45 m) waxed on both the open ends, covered with plastic bags and taped immediately to minimise moisture loss, and which were kept in a vertical upright position at 20 °C maintaining 85 % humidity. Using the collected samples, physicochemical, mineral, microstructural, static and dynamic parameters were evaluated.

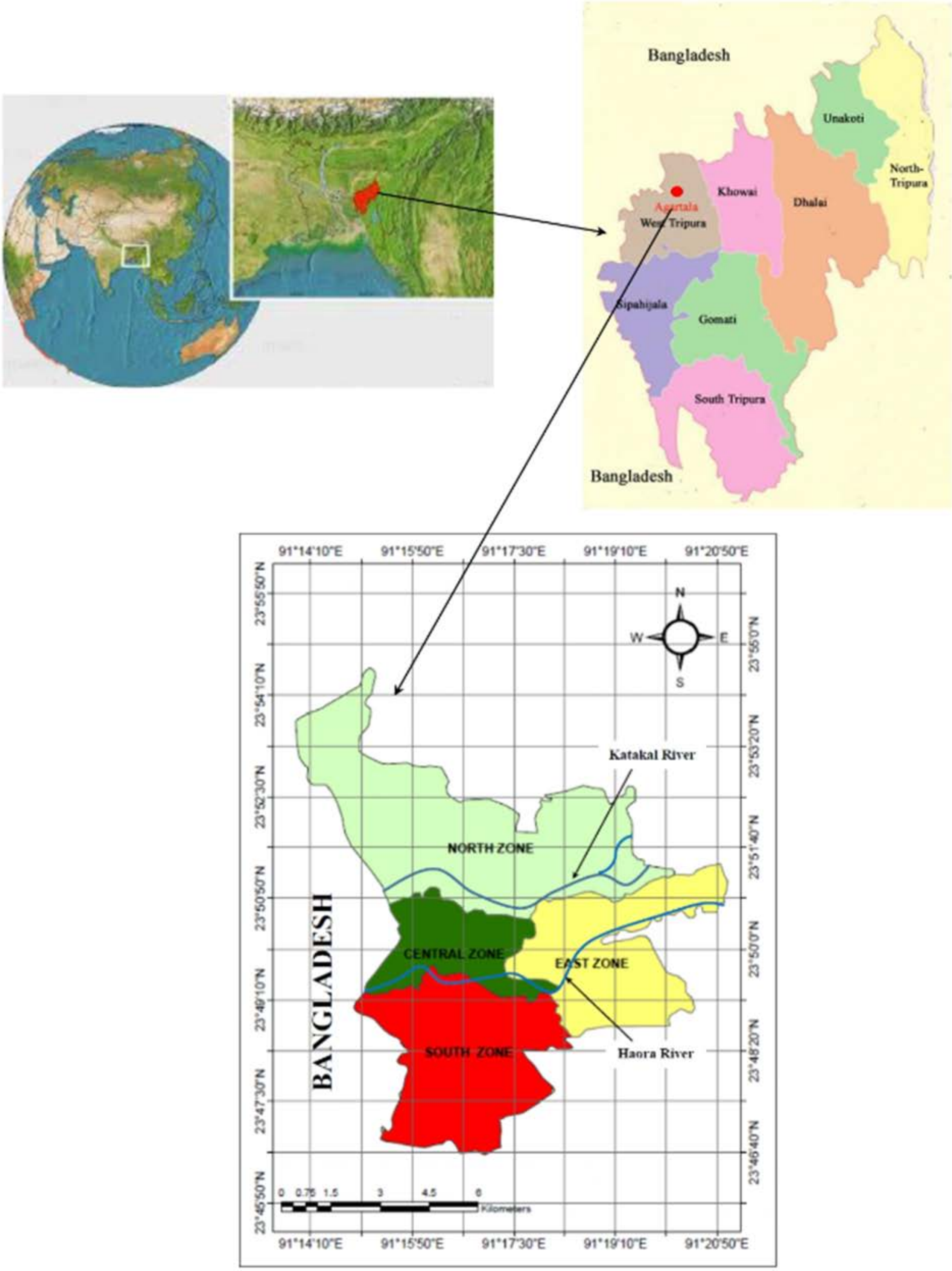

Figure 1. Location maps for the Agartala study area, located in the north-eastern part of India.

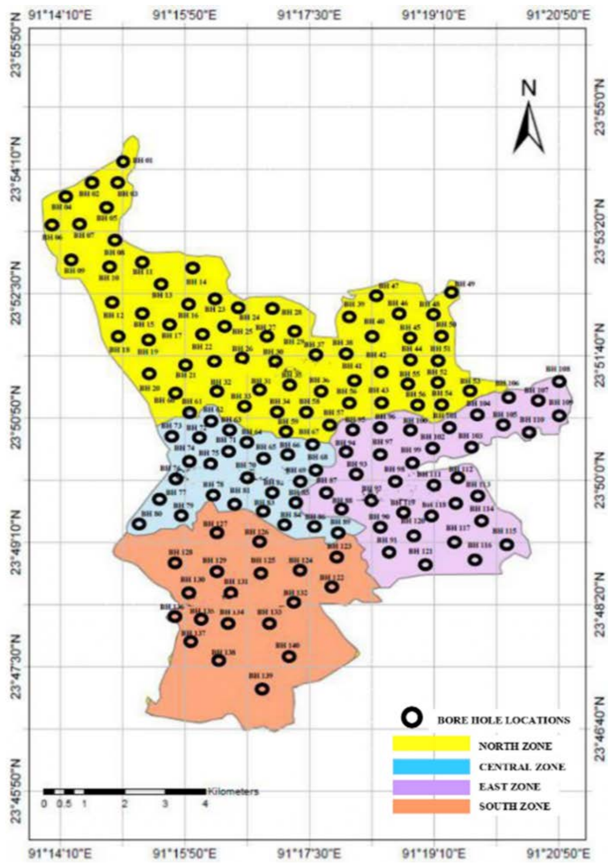

Figure 2. Map of Agartala showing the locations of the 140 boreholes.

Non-destructive testing

Electric resistivity tests (ERT) as per IS 15736 (2007), were conducted at a few locations near the boreholes (15, 16, 17 - north zone; 71, 72 , 73 - central zone; 90, 91, 92 - east zone; 134, 135, 136 - south zone) in order to determine the horizontal continuity of the soil profile by placing electrodes at 1 m, 2 m, 4 m and 6 m in Wenner arrangement (Mohammed *et al*. 2021). A 2D ground resistivity profile was generated using commercially available software Res2Dinvx32 (v.3.71, 2011) (Basri *et al*. 2019).

Laboratory analysis

Peat samples underwent detailed laboratory analysis to determine physicochemical, mineral, microstructural, static and dynamic engineering parameters which are stated below.

The microstructure of peat was evaluated using scanning electron micrographs (SEM). A fine portion of dried peat (0.05 to 0.09 g) was mounted on a copper holder coated with a thin film of gold and placed in a Carl Zeiss lens to evaluate microstructural properties. X-ray diffraction (XRD) was used to obtain the mineralogical composition of the sample, whose particle size was finer than 75 μm.

Physical classification was based on water content (*w*), colour, OM content, fibre content (FC), pH and degree of humification. Colour of peat was ascertained by visual classification as per IS 1498 (1970). Water content was evaluated by oven drying 25 grams of undried peat as outlined in IS 2720 Part 2 (1973). OM content was determined by igniting 50 grams of oven dried peat sample in a muffle furnace at 500 °C for 24 hours, as suggested in ASTM D2974 (2020). FC in peat was determined from fibres retained in a 0.15 mm sieve as per ASTM D1997-91 (2013). The pH of soil was determined using a pH meter (H196107, Hanna instruments) as outlined in IS 2720 Part 26 (1987). Degree of humification was determined according to the von Post scale (von Post 1922).

Both wet sieving and hydrometer analysis were conducted on peat samples, as per IS 2720 Part 4 (1985) to ascertain percentages of sand, silt and clay. Hydrogen peroxide (20 % volume) was used to remove OM present in peat in accordance with IS 2720 Part 4 (1985). However, complete removal of OM may not be possible using this method. The liquid limit of peat was determined using the drop cone method as per IS 2720 Part 5 (1985).

Static and dynamic engineering parameters

UDS were collected from 30 boreholes covering all four zones of Agartala city to evaluate shear strength and settlement parameters of peat. Shear strength in the form of cohesion (c) was evaluated from unconfined compression test (UCC) as per IS 2720 Part 10 (1991), whereas both c and angle of internal friction (ϕ) along with measurement of pore water pressure was determined from consolidated undrained triaxial test (CUTX) in accordance with IS 2720 Part 12 (1981) on samples having 38 mm diameter and 76 mm height. Settlement parameters in the form of compression index (C_c), coefficient of compressibility (a_v), volume compressibility (m_v) and secondary consolidation (C_α) were evaluated by oedometer test on peat samples (60 mm diameter and 20 mm height), as per IS 2720 Part 15 (1965). For hemic peat samples with low permeability, the permeability coefficient (k) was determined using the following equation:

$$k = C_v \times m_v \times \gamma_w \qquad [1]$$

where C_v, m_v are consolidation parameters and γ_w is the density of water.

Dynamic parameters of peat were evaluated from three sets of samples (BH 134, 135, 136) collected from the Indo-Bangladesh region located in the south zone of Agartala whose index and engineering parameters are stated in Table 1, which comprised two set of tests. The first set is comprised of bender element (BE) test to evaluate the shear wave velocity (V_s) of peat samples (50 mm diameter and 100 mm height) under an isotropic confining pressure of 50, 100, 200 and 400 kPa whose detailed procedure can be referred from Leong *et al*. (2009). The shear modulus (G_{max}) was evaluated by applying the following equation:

$$G_{\max} = \rho V_s^2 \qquad [2]$$

where ρ is density of soil specimen, V_s is shear wave velocity maximum. G_{max} is a critical parameter in earthquake geotechnical engineering design which is mainly affected by confining pressure (CP) and void ratio (*e)* as suggested elsewhere (Dammala & Krishna 2018). The available relationships can be classified into the form presented in Equation 3:

$$G_{\max} = A \times F(e) \times P_a^{(1-m)} \times \sigma_c^m \qquad [3]$$

where A is a constant term depending on soil, e is the void ratio, P_a is standard atmospheric pressure, σ_c' confining pressure acting on soil specimen, m is stress dependent factor. The Equation (3) relationship, as proposed by Hardin (1978), has been used widely by other researchers due to its simplicity, dimensional consistency and F(*e*) value which can be used for a wide range, is presented as $1/\left(0.3 + 0.7e_0^2\right)$.

$$G_{\max} = \frac{A \times (P_a)^{1-m} \times (\sigma_c')^m}{\left(0.3 + 0.7e_o^2\right)} \qquad [4]$$

where A is a constant term depending on soil, P_a is standard atmospheric pressure, σ_c' confining pressure acting on soil specimen, e_0 is the initial void ratio and m is stress dependent factor.

Besides, an attempt has also been made to compare the experimentally obtained V_s of peat with empirically calculated in-situ V_s based on SPT. Depth-wise SPT results were used to determine V_s using empirical correlation as suggested by Dikmen (2009), presented in the following equation:

$$V_s = 58N_{60}^{\ 0.39} \qquad [5]$$

where V_s is shear wave velocity maximum, N_{60} is number of hammer blows and 0.39 refers to the exponent of N_{60} proposed by Dikmen (2009).

In the second phase, strain-controlled cyclic triaxial (CTX) tests were performed as per ASTM D3999-91 (2003) on peat samples (38 mm diameter and 76 mm height). Each sample underwent strain-controlled loading in a sequence of 2000 cycles at a loading frequency of 1 Hz, with axial strain varying from 0.2–0.5 %. Axial strain was converted to shear strain with the aid of Poisson's ratio. Figure A1 (in the Appendix) presents a typical hysteresis loop between shear stress and shear strain obtained from strain controlled cyclic loading. Shear modulus (G) is evaluated from the slope and G_{max} is obtained from the BE test. Normalised secant shear modulus ($G/G_{\max}$) helps in distinguishing degradation of the shear modulus with respect to shear strain, and the damping ratio (ξ) is measured from the dissipated energy of a hysteresis loop computed from the following equation:

$$\xi = \frac{\omega_l}{4\pi\omega_h} \qquad [6]$$

where ω_l is area enclosed by the hysteresis loop, while ω_h is area enclosed by hatched region.

Table 1. Index and engineering parameters of peat used for dynamic (Bender element and cyclic triaxial) tests. OM = organic matter, w = water content, γ_{sat} = saturated density, G_p = specific gravity, C_u = cohesion, Ø = angle of internal friction, e_0 = initial void ratio, C_c = coefficient of consolidation.

Borehole No.	Identification of specimen	Description of soil	Particle size distribution (Sand/Silt/Clay) and OM (%)	w (%)	γ_{sat} (g cm^{-3}) $\times 10^{-1}$	G_p $\times 10^{-1}$	LL (%)	Triaxial shear strength parameters (C_u (kN m^{-2}) / ϕ (degrees))	e_0	C_c 10^{-2}
BH 134	Pt(U01134)	Very soft blackish grey peat mixed with clay	0/20/42 (OM-38)	214	14.5	12.6	135	6.4/0	2.69	89.9
BH 135	Pt(U02135)		0/20/45 (OM-35)	204	14.9	12.7	132	7.4/0	2.58	91.8
BH 136	Pt(U03136)		0/24/40 (OM-36)	218	14.1	12.0	140	6.9/0	2.76	93.4

GIS maps based on physical parameters of peat

GIS based maps were developed using ArcGIS (v.10.2.2, 2014). A source map of Agartala city was selected from which shape files were created and then geo-referencing was done. By using the "spatial analyst tool", interpolation of data obtained from the field (depth) and laboratory (OM, *w*, pH) study was conducted to determine the spatial variation across the study area.

Statistical analysis of parameters

Statistical analysis of the database of various peat parameters was performed using Microsoft EXCEL. A menu driven "add-in" function is used to incorporate the "analysis ToolPak" option in EXCEL, and the analysis is carried out by adopting the "Descriptive Statistics" option.

RESULTS

Field test parameters

The N_{60} value of the peat layer at Agartala ranged from 0–6. The peat layer was found at a shallow depth of 0.2–5.0 m, with a few exceptions (Figure 3). Peat at shallow depth was observed in various areas of Agartala town, likewise Krishnanagar, Jaynagar, Paschim Krishnagar, Indranagar, Banamalipur, Jogendranagar, Pratapgarh, Santipara and Badharghat. On the other hand, in places such as Dhaleswar, Ramnagar, Kashipur, Jogendranadar, Shibnagar and Aralia, the peat layer was encountered at greater depth, i.e., 8.0–18.0 m. Resistivity values obtained from ERT tests ranged from 6–83 Ω-m (Figure A2), which also validates the presence of peat deposits at shallow depths.

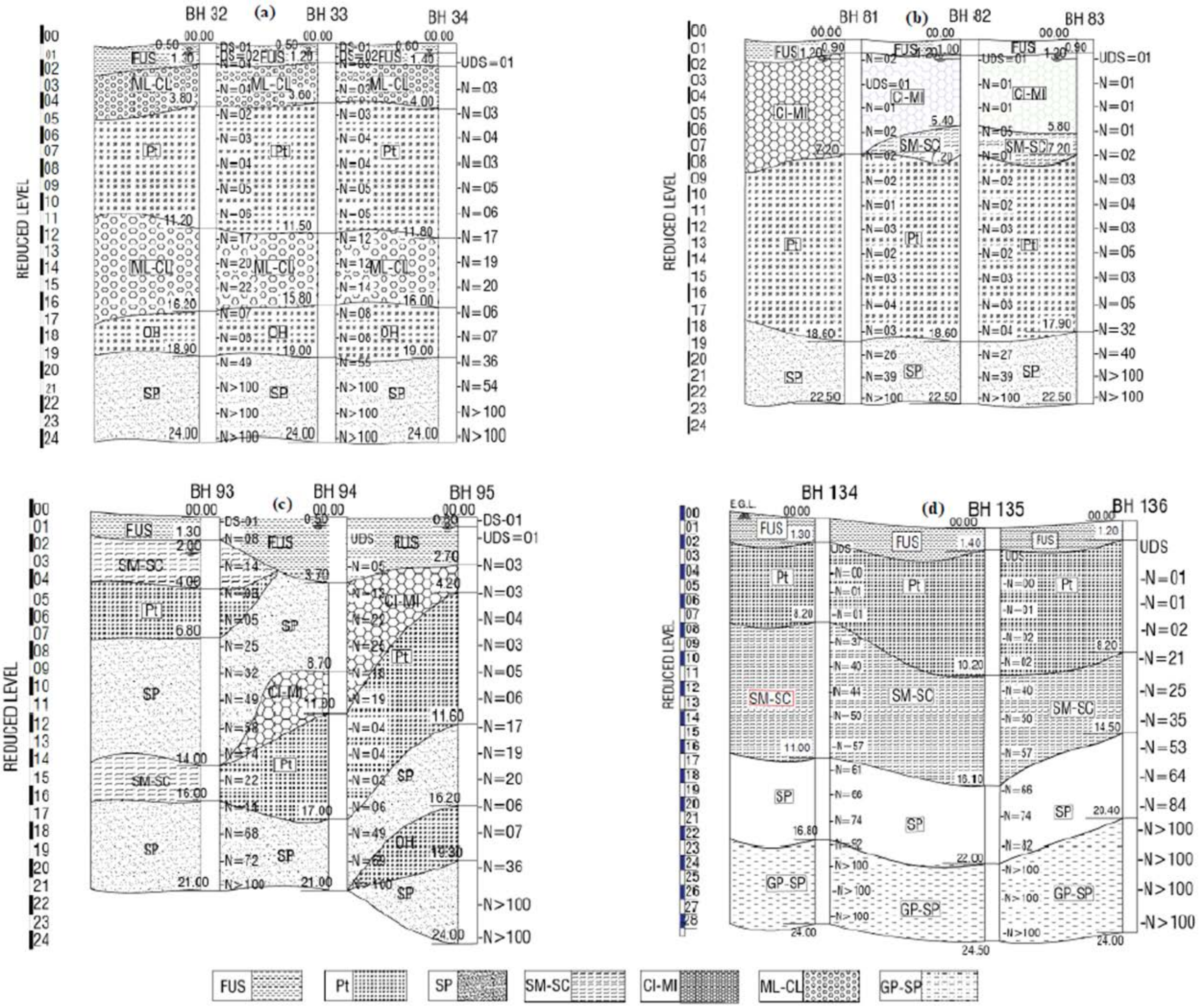

Figure 3. Sample longitudinal cross-sectional subsoil profiles having peat deposits in different zones of Agartala: (a) north zone, (b) east zone, (c) central zone, (d) south zone.

Microstructural and mineralogical composition

Graphs obtained from SEM revealed the microstructure of peat showing dark patches when magnified up to 1,000× indicating voids. Further magnification up to 5,000× and 10,000× showed white patches indicating partially decomposed OM content (Figure 4). Analyses obtained from XRD tests showed that the mineral component of Agartala peat consisted mainly of hydrated halloysite, quartz, feldspar, calcite and clay-sized particles, of which the main constituent is quartz (Figure A3).

Physicochemical parameters

Visually, the colour of the peats varied from dark brown to blackish in nature. Degree of humification determined following von-Post scale ranged from H4–H6. FC varied from 34–55 % and OM content varied from 30–60 %, respectively. From these results, Agartala peat can be classified as a hemic peat. The pH value ranged from 4.4–6.8, and as such the peats be described as moderately acidic. The ranges of other important physical parameters such as w, G and γ_b are presented in Table 2 along with summary statistical data in the form of mean, median, standard deviation (SD) and coefficient of variation (COV). SD and COV varied from 0.09–63.7 % and 12.6–39.6 %, respectively.

GIS maps based on physical parameters of peat

We found that water content is the highest (301 to 410 %) in the eastern zone (Figure 5a). A substantial area of Agartala town has a pH range of 4.5–5.4 mainly in the northern and eastern zone (Figure 5b). The peat depth ranged from 0–6.0 m (shallow) across the majority of Agartala, whereas peat layers were found at greater depth (10–18m) in a few locations in the south and central zone (Figure 5c). The highest content of OM is found mostly in the eastern zone, while the lowest at the edge of the southern and in the middle of the central zone (Figure 5d).

Static engineering parameters

Shear strength parameters (c and ϕ) evaluated from UCC and CUTX test are presented in Table 2. Sample graphs obtained from CUTX are presented in Figures 6a and 6b. Settlement parameters obtained from oedometer tests were presented in the form of C_c which ranges from 0.84–2.12 with e_0 (1.22–3.50). Other settlement parameters such as a_v, m_v and C_α were also evaluated and are presented in Table 2. Sample graphs showing C_c and e_0 values are presented in Figure 6c and 6d respectively and sample graph showing initiation of C_α is presented in Figure 6e respectively. Hydraulic conductivity values obtained using empirical equations are presented in Table 2. Statistical analyses were conducted on static engineering parameters which are presented in Table 2.

Dynamic test parameters

Sample graphs obtained from BE test are presented in Figure A4a, and the convergence ratio (wavepath length/wavelength) L_{tt}/λ for hemic type peat is obtained as 4.40 (Figure A4b) which helps in the precise determination of V_s which ranged from 60.61–76.21 m s^{-1} increased with an increase in CP (Figure A4c). Index and engineering parameters of peat undergoing dynamic testing are presented in Table 3. Variation of G_{max} with increase in CP varied from 5.3–8.7 MPa (Figure A4d).

A comparison of V_s calculated using empirical correlation (Dikmen 2009) and BE test are presented in Table 4. It is observed that V_s obtained from empirical correlation exhibits good agreement with the experimental results with a variation ranging from 9.80–14.5 %.

Cyclic triaxial tests

Figure A5 presents hysteresis loop presenting degradation of peat subjected to cyclic loading at axial strain varying from (0.2 to 0.5 %) under loading

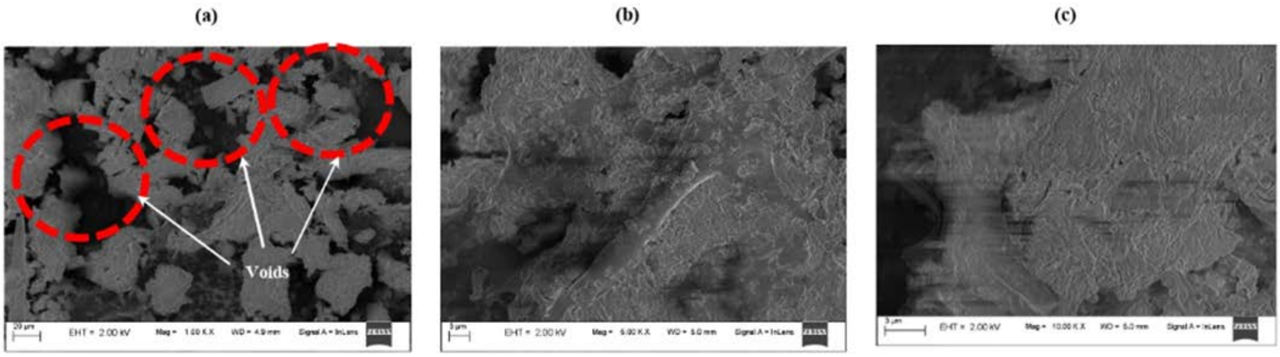

Figure 4. Sample SEM micrographs of Agartala peat at magnification (a) ×1,000, (b) ×5,000 and (c) ×10,000.

cycles ranging from 10 to 2,000 and from the presented graphs it is evident that deviator stress (σ_d) varied from 8–12 kN m^{-2} with an increase in trend with increase in number of cycles. G/G_{max} and ξ values evaluated from hysteresis loop as presented in Figure 7 clearly states a decrease in G/G_{max} value of 0.08 to 0.02 with an increase in strain rate whereas an increase in ξ value from 4.8–6.8 % at similar strain range were obtained for peat samples.

Proposed empirical relationship based on peat parameters (physicochemical and engineering)

Physical parameters in the form of water content, specific gravity, γ_b, *LL* and pH were evaluated and empirical equations were developed with respect to changes in OM content. The water content and *LL* increased linearly with increasing OM content with strong correlation (R^2) values of 0.72 and 0.93, respectively (Figures 8a and 8b). On the other hand,

Table 2. Physiochemical and engineering parameters of Agartala peat samples along with statistical parameters. OM = organic matter, FC = fibre content, pH = potential of hydrogen, G_p = specific gravity, γ_b = bulk density, *LL* = liquid limit, C_u = cohesion, Ø = angle of internal friction, C_c = compression index, *e* = void ratio, a_v = coefficient of compressibility, C_v = coefficient of consolidation, C_α = secondary consolidation, m_v = volume compressibility, RC = ratio of compression, CR = compression ratio, *k* = permeability coefficient, SD = standard deviation, COV = coefficient of variation, NA = not applicable.

Parameters	Range	Statistical parameters			
		Mean	Median	SD	COV (%)
OM (%)	30–60	36.3	36.0	5.8	16.0
FC (%)	34–55	35.1	36.4	6.1	17.4
pH	4.4–6.8	5.5	5.5	0.7	12.0
Humification	H4–H6	NA	NA	NA	NA
Water content (%)	65–410	165	159	63.7	38.6
Particle size distribution (Sand, Silt, Clay) and OM (%)	Sand: 2–5 Silt: 18–22 Clay: 30–48 OM: 30–60	-	-	-	-
G_p (g cm^{-3})	1.2–1.8	1.4	1.3	0.2	12.7
γ_b (g cm^{-3})	1.1–1.4	1.3	1.4	0.1	6.7
LL (%)	95–210	149	138	42.3	28.4
C_u- UCS (kN m^{-2})	5.4–18.1	13.2	13.9	3.72	28.2
C_u- CUTX (kN m^{-2})	3.7–14.7	12.1	12.2	3.9	31.9
Ø	1–10°	4.4	4.5	2.4	53.5
C_c	0.8–2.1	1.1	1.0	0.2	18.3
e	1.2–3.5	2.7	2.7	0.5	17.9
$a_v \times 10^{-4}$ (m^2 kN^{-1})	16.2–20.5	-	-	-	-
$m_v \times 10^{-4}$ (m^2 kN^{-1})	10.6–13.5	-	-	-	-
$C_v \times 10^{-9}$ (m^2 s^{-1})	0.2–1.6	-	-	-	-
$C_\alpha \times 10^{-2}$	3.1–5.9	2.8	2.4	1.1	1.2
RC=$(C_\alpha/C_c) \times 10^{-2}$	1.9–2.8	2.2	2.1	0.4	0.39
CR=$(C_c/(1+e_o))$	0.3–0.4	0.3	0.3	0.1	25.8
$k \times 10^{-11}$ (cm s^{-1})	2.1–2.7	-	-	-	-

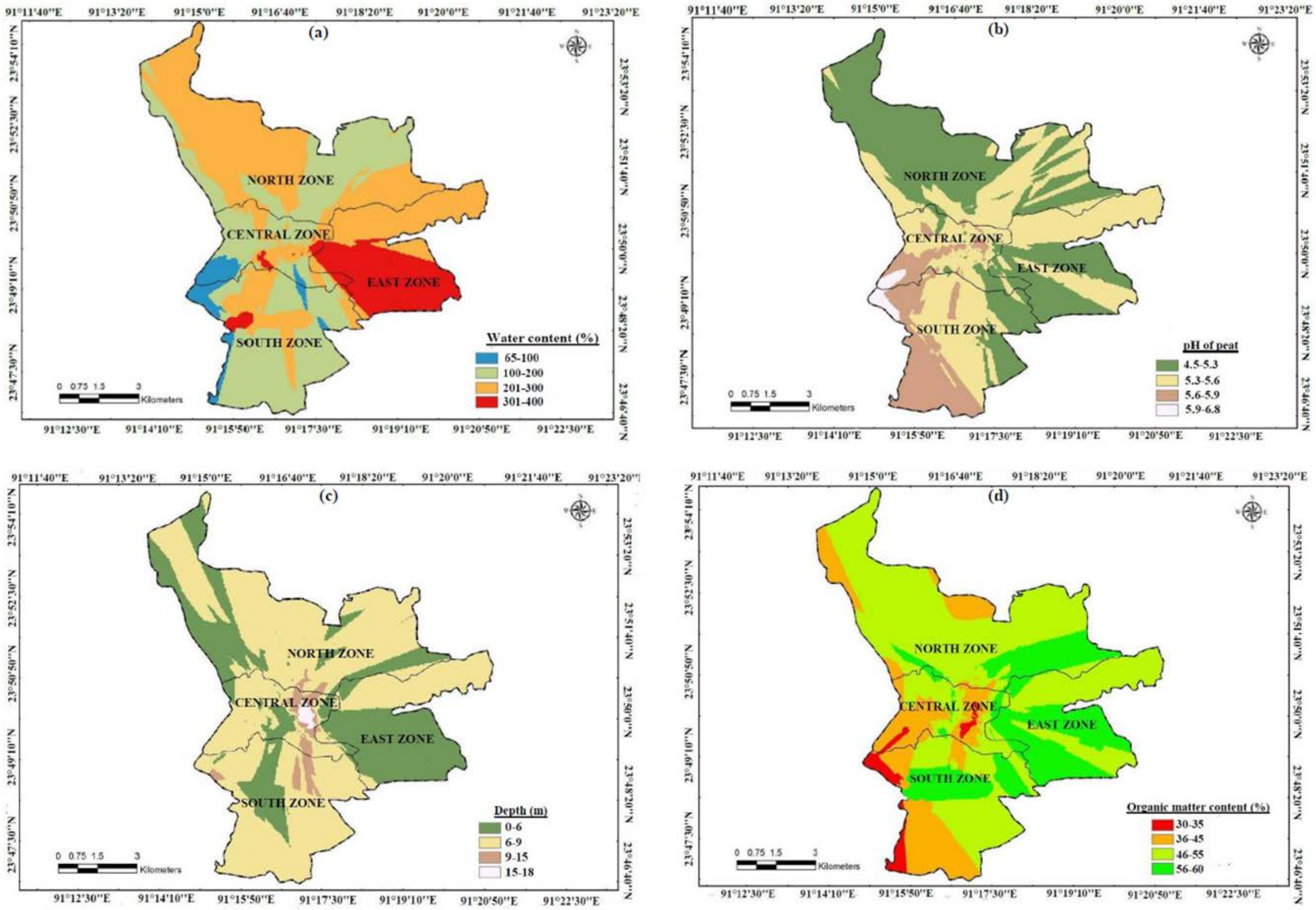

Figure 5. GIS maps presenting the spatial variation of various properties of peat:- (a) water content; (b) pH; (c) depth; and (d) organic matter content.

the specific gravity and pH decreased linearly with increases in OM content and empirical equations are developed between specific gravity, pH and OM with R^2 values of 0.68 and 0.72, respectively (Figure 8c and 8d). Empirical equations were also developed for shear settlement parameters of peat. Variation of the settlement parameter C_c with *LL* (which varied linearly with OM) were evaluated - R^2 = 0.68 (Figure 8e). Variation of C_c with respect to C_α was also evaluated, which showed a linearly increasing trend, having an R^2 value of 0.82 (Figure 8f). Further, correlations were also proposed for γ_b and cohesion which tends to decrease with OM content having correlation values of 0.88 and 0.92 (Figures A6a and A6b). Whereas *e* (which tends to increase with OM content) has a linearly increasing trend with respect

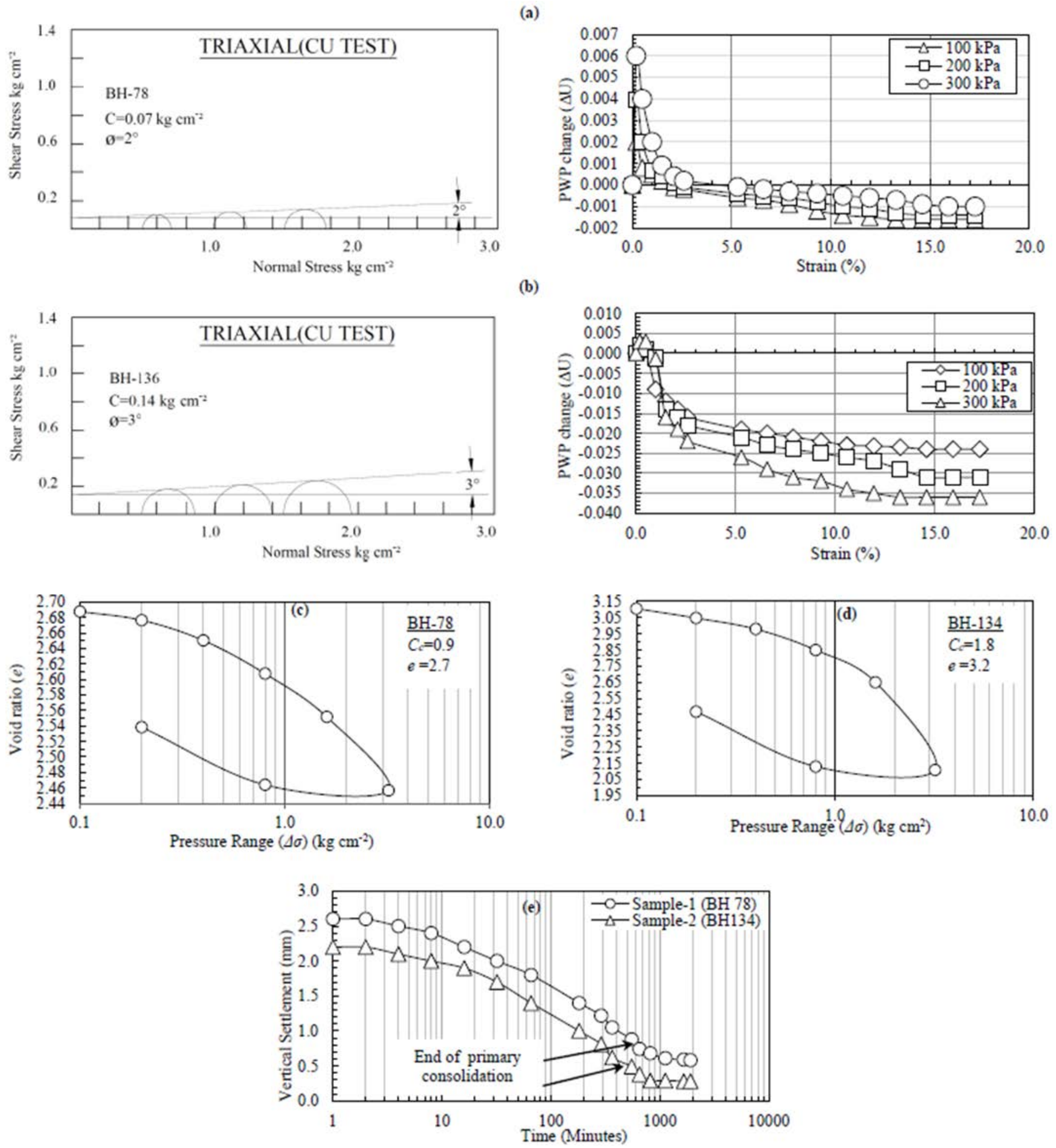

Figure 6. Sample graphs with static engineering parameters, shear strength parameters and measurements of pore water pressure (PWP) for peat samples collected from two sites in Agartala town, obtained from consolidated undrained triaxial (CUTX) test: (a) BH-79 and (b) BH-136; and settlement parameters from consolidation test: (c) BH 78, (d) BH 134 and (e) time settlement curves.

Table 3. Comparison of V_s obtained from empirical relationship based on SPT and laboratory at similar effective stress. b.g.l = below ground level, SPT = standard penetration test, V_s = shear wave velocity, BE = bender element.

Borehole No.	Identification of specimen	Depth of sample (m b.g.l)	SPT value	V_s obtained from correlation proposed by Dikmen (2009) with SPT value (m s-^{1})	V_s obtained from BE test (m s^{-1})	Variation (%) between Dikmen (2009) and SPT value
BH 134	Pt(U01134)	3.0	01	58.0	64.4	11.0
BH 135	Pt(U02135)	4.5	01	58.0	66.0	14.5
BH 136	Pt(U03136)	6.0	02	76.0	69.2	9.8

Table 4. Proposed empirical equations and comparison with available relationships reported in past studies. OM = organic matter, pH = potential of hydrogen, w = water content, G_p = specific gravity, γ_b = bulk density, LL = liquid limit, C_u = cohesion, Ø = angle of internal friction, C_c = compression index, e = void ratio, C_α = secondary consolidation, m_v = volume compressibility, G_{max} = maximum shear modulus, σ_c' = confining pressure.

Parameters	Empirical equations proposed from present study	Empirical equations proposed by researchers
OM *vs.* w	OM = 0.0771(w) + 23.516; R^2 = 0.71;	OM = 0.0592(w) + 54.34, (Huat *et al.*2009, Malaysia); OM = 0.0952(w) + 22.47, (Paul *et al.* 2018, NE India);
e *vs.* w	e = 0.0144 (w) + 0.7316; R^2 = 0.78;	e = 0.016 (w) + 0.819, (Badv & Sayadian 2012, Italy);
pH *vs.* OM	OM = -7.7442(pH)+79.152; R^2 = 0.78;	OM = 51(pH) – 59, (Helling *et al.*1964, USA);
OM *vs.* γ_b	OM = 72.654(γ_b)$^{-2.337}$; R^2 = 0.88;	OM = 57.26(γ_b)$^{-4.9032}$, (Huat *et al.*2009, Malaysia);
G_p *vs.* OM	G_p = -0.0238(OM) + 2.28442; R^2 = 0.68;	G = -0.013(OM) +2.462, (Paul *et al.* 2018, NE India); G = 0.0082(OM) + 2.14, (Duraisamy *et al.* 2009, Malaysia); G = 5.2636(OM)-0.2848, (Huat *et al.* 2009, Malaysia); OM = -71.84(G) +193.9, Badv & Sayadian 2012, Italy);
OM *vs.* LL	OM = 0.1421(LL) + 15.663; R^2 = 0.93;	OM = 0.1750(LL) + 20.37, (Huat *et al.* 2009, Malaysia); LL=0.2088(OM) +59.982, (Kolay *et al.* 2010, Malaysia)
e *vs.* LL	e = 2.1187ln (LL) – 7. 8718; R^2 = 0.88;	e = 3.2093 ln (LL) – 11.835, (Huat *et al.*2009, Malaysia);
C_u *vs.* OM	C_u = -0.0587 OM + 3.3757; R^2 = 0.93;	C_u= 3.35 OM+115.37, (Kolay & Animur 2015, Malaysia)
C_c *vs.* LL	C_c = 0.0061(LL-10) + 0.26; R^2 = 0.69;	C_c = 0.009(LL-10), (Terzaghi and Peck.1967, USA);
C_c *vs.* w	C_c = 0.1529$w^{0.3854}$; R^2 = 0.46;	C_c = 0.0065w,(Hobbs *et al.* 1986, UK); C_c = 0.01w, (Badv & Sayadian 2012, Italy);
C_α *vs.* C_c	C_α = 0.032 C_c; R^2 = 0.82;	C_α = 0.036 C_c (Hebib & Farrell 2003, Ireland); C_α = 0.038 C_c, (Mesri *et al.* 2007, USA); C_α = 0.097 C_c, (Santagata *et al.* 2008, USA); C_α = 0.027 C_c, (Duraisamy *et al.* 2007, Malaysia); C_α = 0.038 C_c (Reddy *et al.* 2013, India); C_α = 0.018 C_c (Varghese *et al.* 2019, India)
G_{max} *vs.* σ_c'	$G_{max} = A \times F(e) \times (\sigma_c')^m$	$G_{max} = A \times F(e) \times (\sigma_c')^m$, A=75.7, m=0.8; (Wehling *et al.* 2003, USA)

to water content and *LL*, with R^2 values of 0.75 and 0.82 (Figures A6c and A6d). Variation of water content with C_c is also reported which tends to linearly increase having R^2 value of 0.45 (Figure A6e). G_{max} is another vital dynamic parameter evaluated from BE tests which tends to vary with CP and *e*. The BE test results are best fitted using a nonlinear regression equation, which helps to develop a correlation of G_{max} and σ_c'. Figure A6f presents the proposed empirical equation.

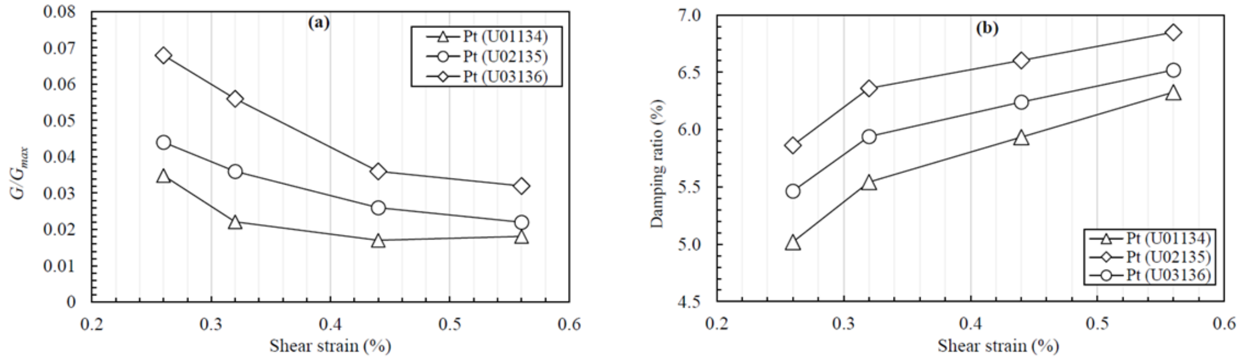

Figure 7. Dynamic parameters of Agartala peat :- (a) Variation of secant shear modulas (G/G_{max}) with respect to shear strain range of 0.26 to 0.55 %. (b) Damping ratio (%) within strain range 0.26 to 0.55 %.

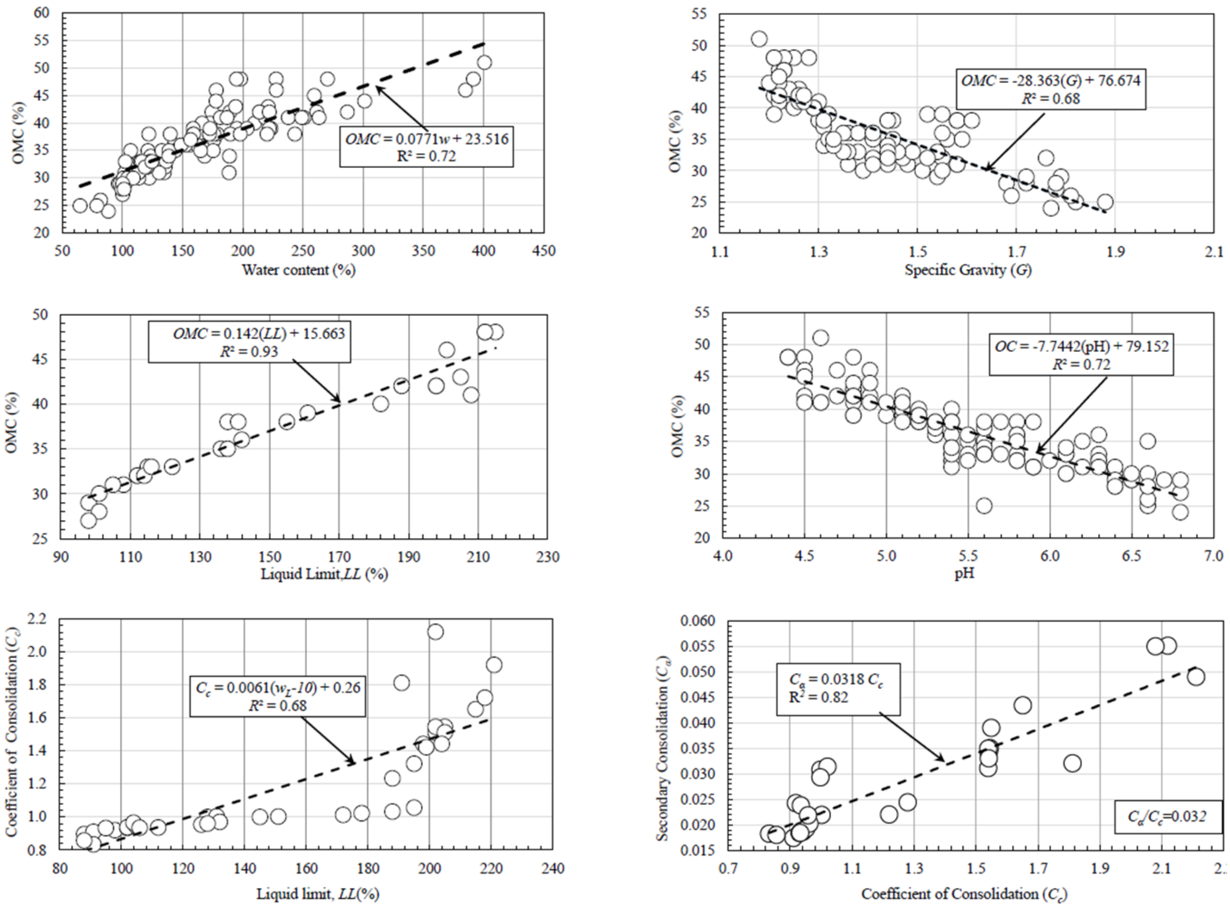

Figure 8. Proposed empirical equations of physical and engineering properties obtained for Agartala peat: (a) organic matter content (OMC) with water content; (b) Organic matter content (OMC) with specific gravity (G); (c) Organic matter content (OMC) with Liquid limit (LL); (d) Organic matter content (OMC) with pH; (e) Coefficient of consolidation (C_c) with liquid limit (LL); (f) Secondary consolidation (C_α) with coefficient of consolidation (C_c).

DISCUSSION

Field test results (SPT and ERT)

SPT values are indicative of engineering characterisation and depth of peat. The range of N_{60} recorded in the present study from 0 to 6 agrees well with the results reported for USA and Malaysian peats by Allgood *et al.* (2003) and Al-Ani *et al.* (2013). Such low values of N_{60} are mainly attributed to the presence of OM, presence of voids, and the low density of the peat. Further, field ERT results evaluated from the present study (in the range of 6–90 Ω-m) are similar to values for Polish and Malaysian peats reported by Maślakowski *et al.* (2014) and Basri *et al*. (2019), respectively. These field experiments will provide a preliminary basis for the selection of foundation systems, and will inform potential ground improvements prior to the construction of infrastructure in this region.

Microstructural and mineral composition

SEM graphs of Agartala peat samples had prominent dark patches indicating voids accompanied by flaky natural material. The morphology of Agartala peat was similar to that found by Kolay & Animur (2015), Paul & Hussain (2019) and Khanday *et al.* (2021) for the peat samples collected from Malaysia and north-east India respectively. Micrographs indicated the peat to be moderately decomposed having large voids and a similar inference was made by Rahgozar & Saberian (2015) and Paul & Hussain (2019). The mineralogical composition of Agartala peat revealed good conformity with the findings of previously published work (e.g., Moayedi *et al.* 2014, Paul & Hussain 2019, Khanday *et al*. 2021) which also confirmed quartz as the main material component present in the peats.

Physicochemical parameters

Peat tends to have a wide range of *w* varying from 60–1,000 % (Cola & Cortellazzo 2005, Ozcan *et al*. 2020, Zimar *et al.* 2020, Paniagua *et al.* 2021). It is likely that such high amounts of water are due to the presence of pores and high water retention capacity. The presented results fall well within the range published in previous literature. Specific gravity obtained in the present study (varies within a range of 1.22–1.42) is found to be a close match with peats in Malaysia, Sri Lanka and France (Latifi *et al.* 2016, Zimar *et al*. 2020, Kalantari 2013). The OM content in Agartala peat was found to be in the range 30–60 % and matches well with results for Turkish peat (47–58 %; Ulusay *et al.* 2010), Iranian peat (25–75 %; Badv & Sayadin 2012) and Sri Lankan peat (22–54 %; Zimar *et al.* 2020). The moderately acidic nature of Agartala peat is also in agreement with the pH range of peats reported elsewhere (Hebib & Farrell 2003, Deboucha & Hashim 2009, Khanday *et al.* 2021). The bulk density of hemic Agartala peat (1.09–1.40 g cm^{-3}) was similar to the counterpart range properties of peat from countries like Italy, China and Sri Lanka (Cola & Cortellazzo 2005, Nie *et al.* 2012, Zimar *et al.* 2020). Such low values of bulk density can mainly be attributed to the porous structure and OM content present in peat. The liquid limit (*LL)* of peat tends to vary depending upon the type of peat, but tends to be high mainly due to its water retention capacity resulting from the presence of abundant OM. The *LL* of Agartala peat exhibited good similarity with results obtained from Malaysia, Turkey, other parts of India and the USA, which varied within a range of 140–260 % (Huat *et al.* 2004, Kalantari & Huat 2009, Celik & Canakci 2014, Ali 2016). Finally, Table A1 (in the Appendix) presents a detailed comparison of the physicochemical properties of Agartala peat with equivalent results from other regions obtained from previously published literature.

GIS maps based on various parameters of peat

GIS based maps highlighting spatial variation of physical, chemical characteristics and depth of occurrence of peat deposits across Agartala town help to provide preliminary information to engineers and planners for identifying the high peat content sites. Accordingly, remedial solutions may be worked out in advance for future construction. However, it has been already experienced that some existing buildings have undergone significant differential tilting in areas with substantial peat layers in Agartala. Hence, the outcome of present study is important for future construction projects in Agartala.

Static parameters

Low values of shear strength parameters (c and ϕ) of Agartala peat is due to the presence of voids, degree of humification, and OM content in peat, which was also reported in previous studies (e.g., Long 2005, Latifi *et al.* 2016, Rahman *et al.* 2016, Zimar *et al*. 2020). Observed c and ϕ of 3.73–14.71 kN m^{-2} and 1–10°, respectively showed good resemblance with the counterpart results reported by Kazemian *et al.* (2012), Paul & Hussain (2019), Zimar *et al.* (2020).

Settlement parameters such as C_c of peat samples are found to be comparable with results reported by Islam *et al.* (2004), Ulusay *et al.* (2010), Zimar *et al.* (2020) with C_c value ranging from 0.33–2.42 for Bangladesh, Turkey and Sri Lanka respectively. Such high settlement values are mainly due to higher *e*, which ranged from 1.16–3.28 and presence of OM. High values of a_v, m_v and C_v parameters evaluated from Agartala peat and similar ranges were reported for Nigerian, Turkish and Indian peat (Ulusay *et al.* 2010, Adejumo 2012, Paul & Hussain 2019). The C_α range of Agartala peat exhibited a close agreement with the results presented by Fox *et al.* (1992), Ulusay *et al.* (2010), Wong *et al.* (2016) for USA, Turkey and Malaysia, respectively. The compression ratio (C_c/1+e_0) and ratio of compression (C_α/C_c) of Agartala peat yielded similar results to those reported by Hebib & Farrel (2003), Moa *et al.* (2009) and Varghese *et al.* (2019) for peats in Italy, Malaysia and India, respectively. As per O'Loughlin & Lehane (2003), when (C_c/1+e_0) of soil exceeds 0.20, the soil is termed as highly compressible and results obtained from the present study ranged from 0.38–0.47 which indicates high settlement potential.

Hydraulic conductivity values calculated using empirical equation were found to be in close agreement with the counterpart results reported by Santagata *et al.* (2008), Reddy *et al.* (2014), Paul & Hussain (2019) for USA, Kolkata (India) and north-east Indian peats, respectively. Such low permeability values were mainly attributed to the water retention capacity and OM content of hemic peat, which hinders the flow of water. Table A2 presents comparisons with the results obtained by various researchers which may help to contextualise the characteristics of Agartala peat.

Dynamic parameters

Dynamic parameters recorded from BE tests in the form of V_s and G_{max} for Agartala peat ranged from 11 to 129 m s^{-1} and 4.77–18.80 MPa, exhibits close agreement with the range of values reported by Kishida *et al.* (2008), Trafford & Long (2020), and Sarkar & Sadrekarimi (2020) for USA, Ireland and Canada respectively. Such low values are mainly explained by high water content, low unit weight and a porous structure. Further, the validation study of prediction of V_s using an empirical equation (Dikmen 2009) based on N_{60} offers sanctity of the used relationship for calculating V_s for Agartala peat in case of non-availability of laboratory test results.

G/G_{max} and ξ values obtained from CTX were found to be in close match with the values reported by Kramer (2000) and Moreno & Rodrigue (2004) obtained in the USA and Colombia which can be adopted for carrying out ground response studies.

Proposed empirical correlations

Empirical equations were developed based on physical, chemical, static and dynamic parameters of peat which will help in better understanding the variation of physical parameters (water content, *LL*, specific gravity, pH, γ_b) with changes in OM content. Variation in the shear strength parameter (*c*) with OM content were also examined and correlations of settlement parameters (C_c and C_α) were also evaluated which can allow a quick estimation of these parameters in the absence of test results.

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AUTHOR CONTRIBUTIONS

Fieldwork and laboratory testing were performed by RD. Visualisation and conceptualisation of the problem, review, formatting and editing of the manuscript were jointly conducted by RD, RS and SH.

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Appendix

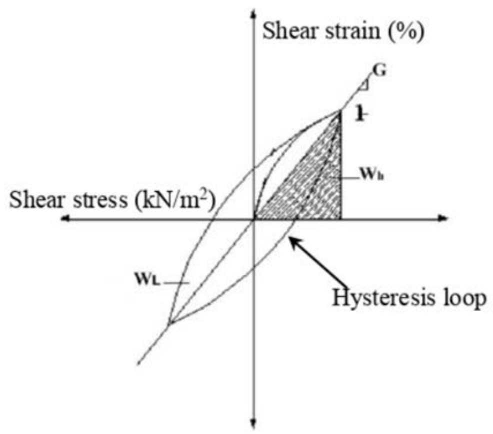

Figure A1. Hysteresis loop obtained from cyclic loading (Jaya *et al*. 2012).

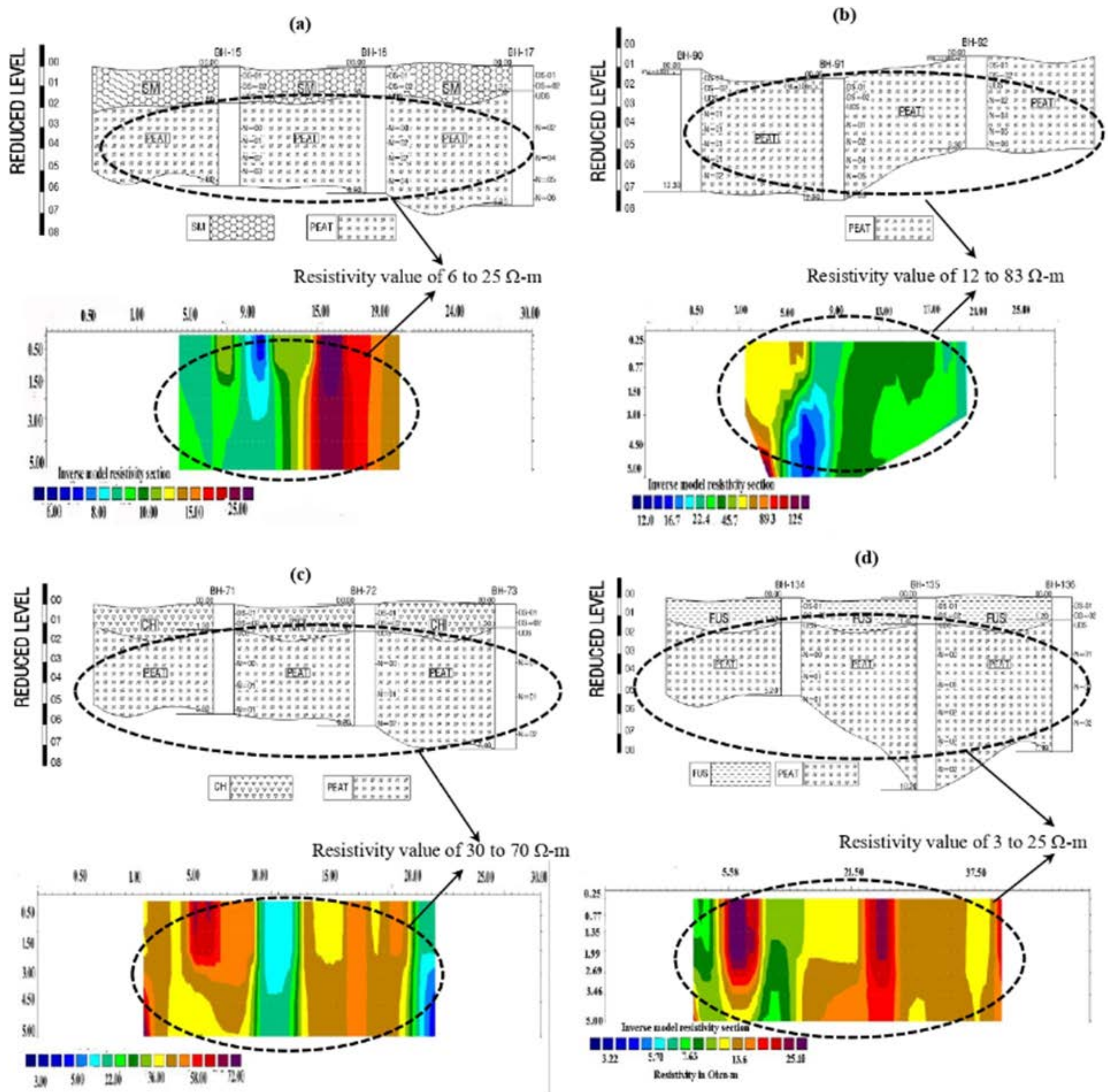

Figure A2. 2D resistivity profile obtained from electric resistivity tests which are validated with subsoil profile for four zones of Agartala town: (a) north zone, (b) east zone, (c) central zone and (d) south zone.

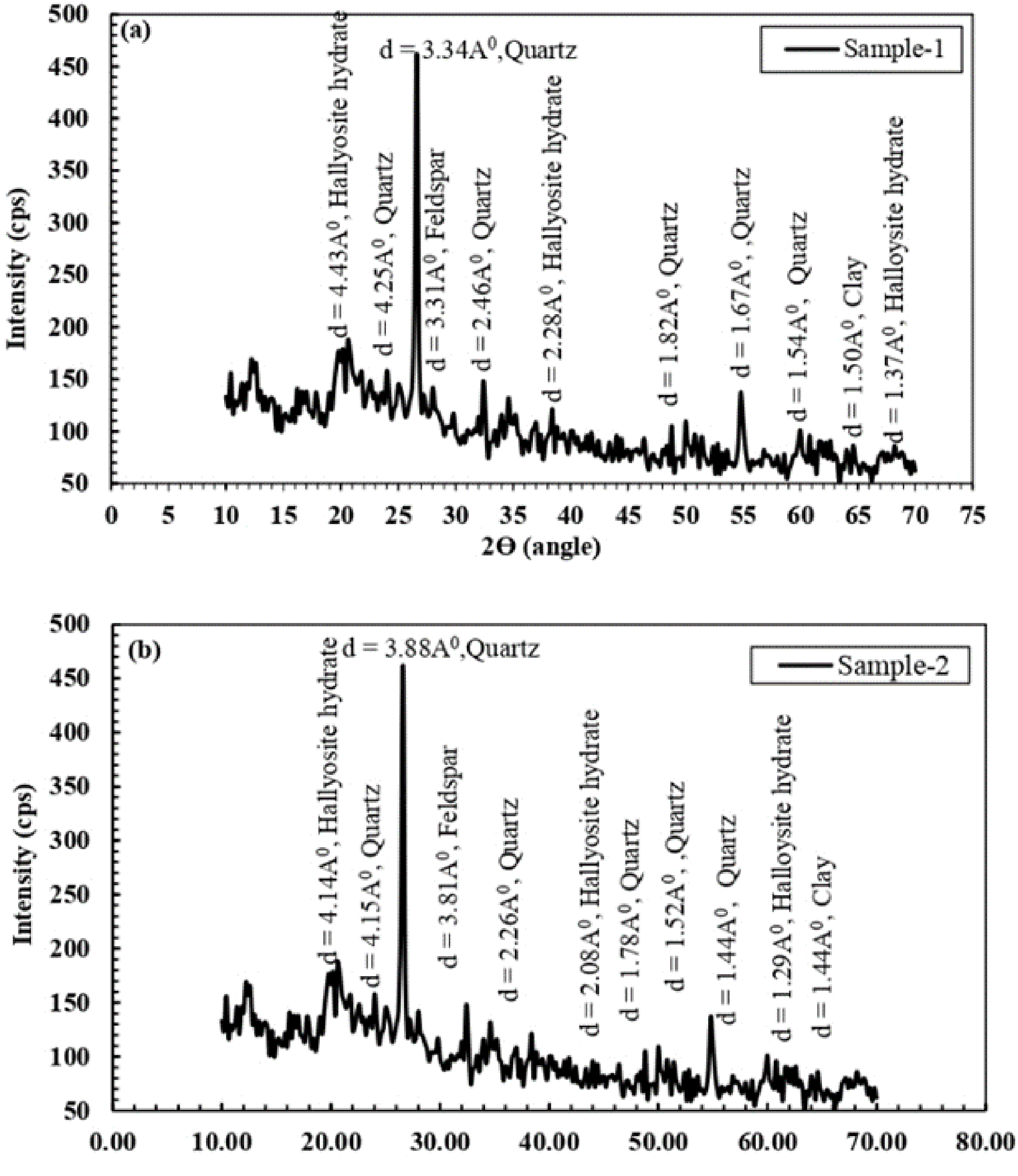

Figure A3. Sample graphs of XRD analysis conducted on soils collected from two locations in Agartala town: (a) Sample 1 (BH 60) and (b) Sample 2 (BH 79).

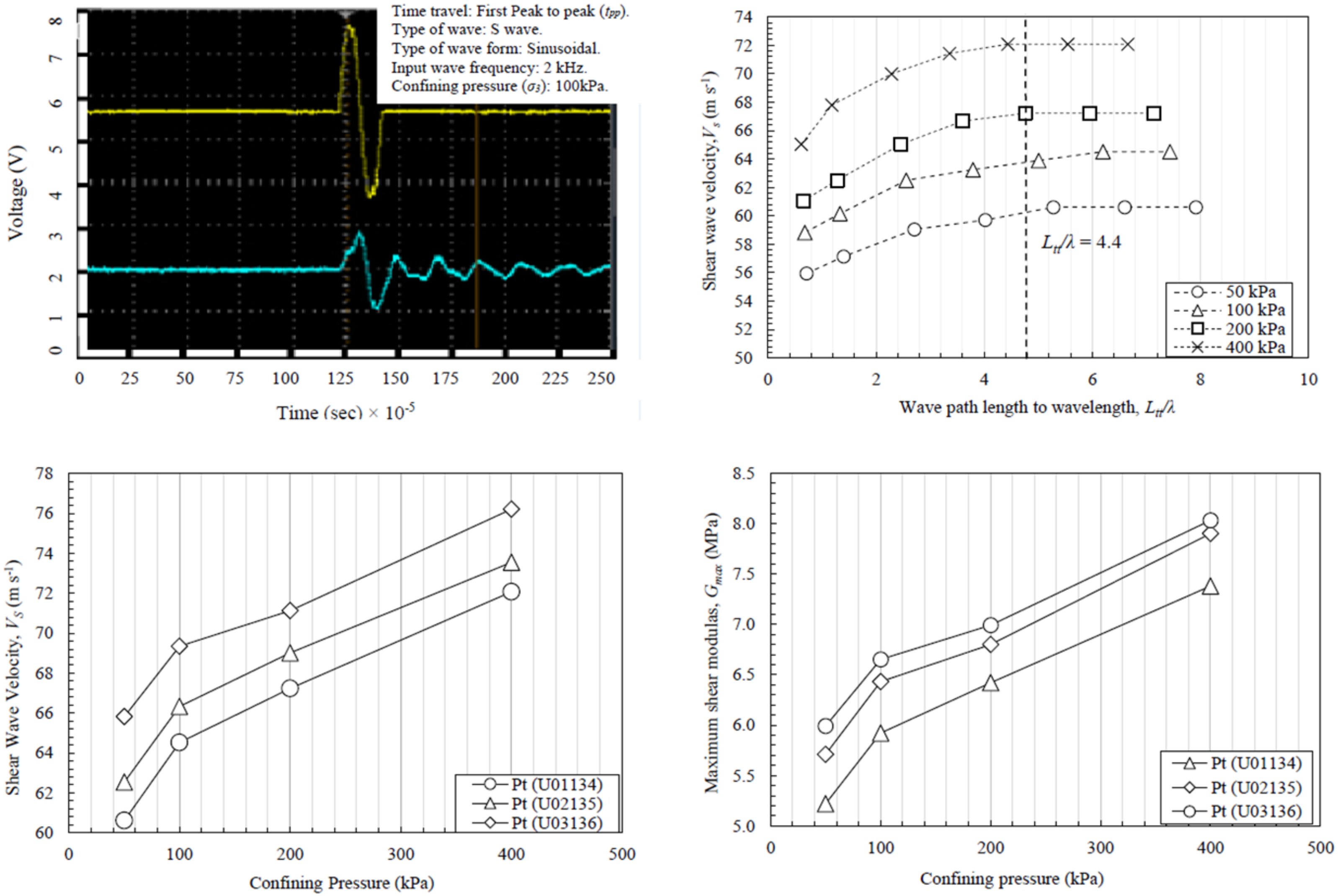

Figure A4. (a) Sample results of bender element test: (b) effect of L_{tt}/λ ratio on shear wave velocity (V_s) under confining pressure of 50, 100, 200 and 400 kPa, (c) comparison of shear wave velocity (V_s) at different confining pressures for Agartala peat, (d) variation of small strain shear modulus (G_{max}) with confining pressure for Agartala peat.

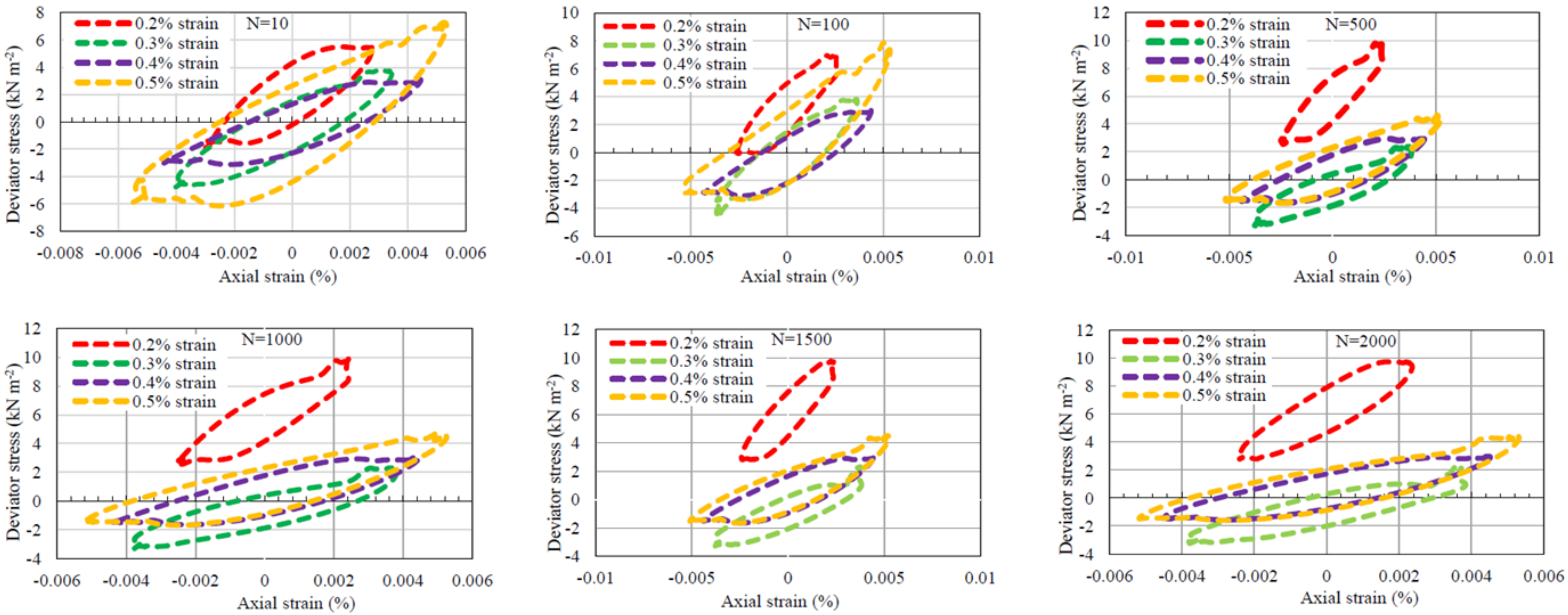

Figure A5. Sample graphs showing degradation of peat under cyclic loading at 0.2, 0.3, 0.4 and 0.5 % axial strains in varying cylces of loading (*N*) ranging from 10 to 2000.

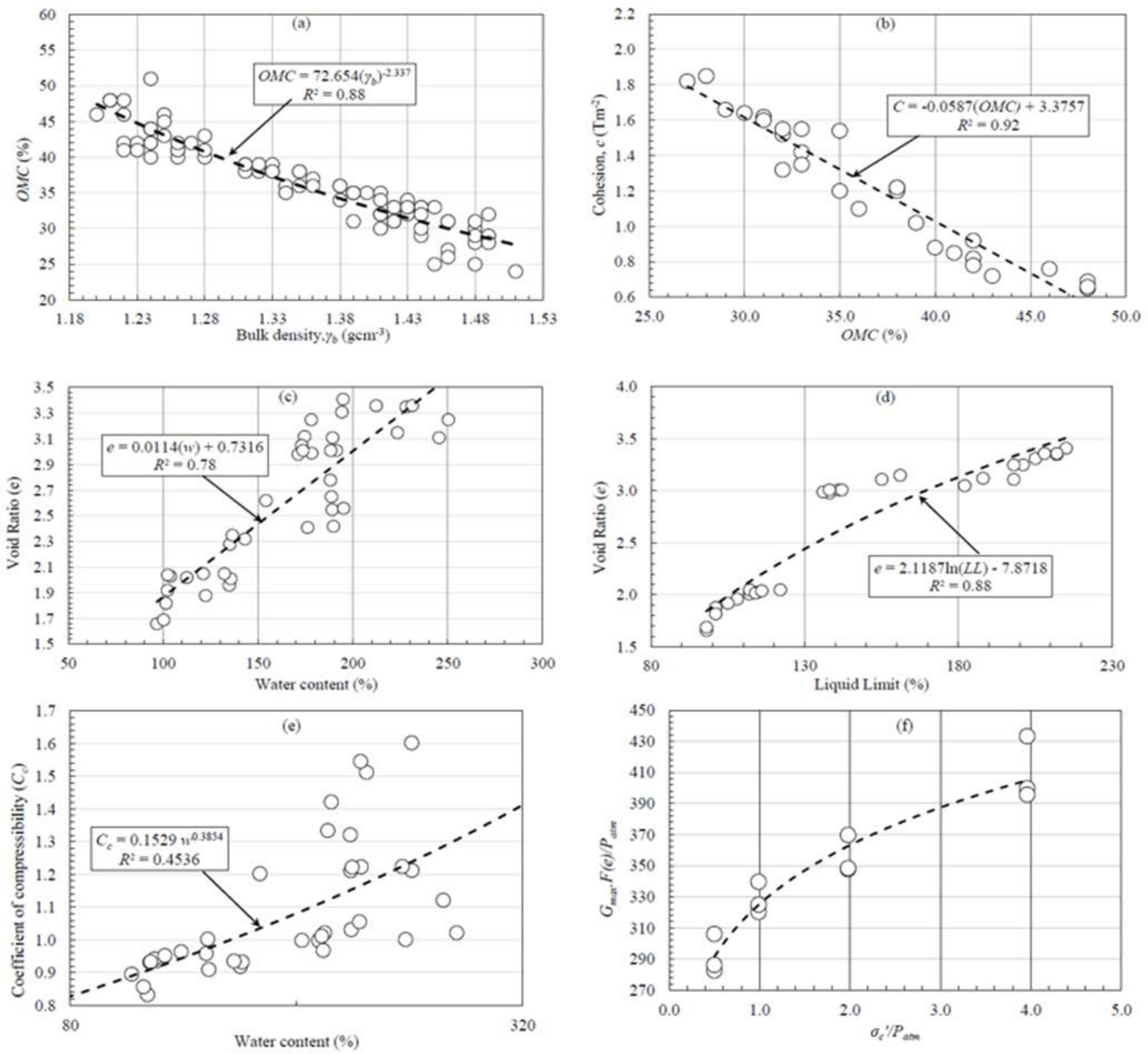

Figure A6. Proposed empirical equations of physicochemical parameters for Agartala peat: (a) bulk density with organic matter content (OMC), (b) cohesion with OMC, (c) void ratio with OMC, (d) void ratio with liquid limit, (e) coefficient of compressibility with water content, (f) proposed best-fit G_{max} relationship equation for Agartala peat.

Table A1. Physiochemical properties of peat samples. OM = organic matter, FC = fibre content, pH = potential of hydrogen, w = water content, G_p = specific gravity, γ_b = bulk density, LL = liquid limit.

Parameters	Code/ Method	Range	Data retrieved from published literature along with their study area
OM (%)	ASTM D 2974-2020	30–60	17–80 (Huat *et al.* 2004, Malaysia), 35–85 (Nie *et al.* 2012, China), 33 (Chowdhury *et al.*2016, Bangladesh), 47–58 (Ulusay *et al.* 2010, Turkey), 25–75 (Badv *et al.*2012, Iran), 43 (Kolay *et al.*2015, Malaysia)
FC (%)	ASTM D 1997-2013	34–55	31–77 (Duraisamy *et al.* 2009, Malaysia), 41.9 (Moayedi *et al.* 2014, Malaysia), 37 (Paul *et al.* 2018, NE India)
pH	IS:2720-26 (1987)	4.4–6.8	4.0–7.2 (Cola *et al.* 2005, Italy), 4.6 (Deboucha *et al.* 2009, Malaysia), 4.1–6.2 (Kolay *et al.* 2015, Malaysia), 4.9–5.3 (Hebib *et al.* 2003, Ireland), 5.3 (Latifi *et al.*2016, Malaysia)
Humification	von Post (1992)	H4–H6	-
w (%)	IS:2720-2 (1973)		310–421 (Cola & Cortellazo.2005, Italy), 135–322 (Ulusay *et al.*2010, Turkey), 159 (Moayedi *et al.*2013, Iran), 110 (Chowdhury *et al.* 2016, Bangladesh), 256 (Celik *et al.* 2014, Turkey); 150 (Latifi *et al.* 2016, Malaysia)
Particle size distribution (Sand, Silt, Clay) and (organic matter, OM) (%)	IS:2720-4(1973)	Sand: 2–5 Silt: 18–22 Clay: 30–48 OM: 30–60	-
G_p	IS:2720-3-1 (1980)	1.2–1.8	1.4–1.6 (Cola & Cortellazo 2005, Italy), 1.3–1.7 (Huat *et al.* 2004, Malaysia), 1.2–1.8 (Kolay *et al.* 2015, Malaysia), 1.4 (Latifi *et al.* 2016, Malaysia), 1.2 (Kalantari 2013, India); 1.2–1.5 (Adnan *et al.*2017, Malaysia)
γ_b (g cm^{-3})		1.1–1.4	1.1–1.3 (Ullusay *et al.* 2010, Turkey), 1.0–1.4 (Huat *et al.* 2004, Malaysia), 0.9–1.2 (Kazemian *et al.* 2012, Malaysia), 0.9–1.1 (Cola *et al.* 2005, Italy), 1.0–1.1 (Paul *et al.* 2019, NE India), 0.9–1.1 (Nie *et al.*2015, China)
LL (%)	IS:2720-5 (1985)	95–210	140–300 (Huat *et al.* 2004, Malaysia), 125 (Celik *et al.*2014, Turkey), 160 (Kalantari & Huat 2009, India), 174 (Deboucha & Hashim 2009, Malaysia), 260 (Ali 2016, USA); 78–95 (Animur *et al.* 2009, Malaysia)

Table A2. Static engineering parameters of Agartala peat. C_u = cohesion, Ø = angle of internal friction, C_c = coefficient of compression, e = void ratio, G_p = specific gravity, γ_b = bulk density, LL = liquid limit, , a_v = coefficient of compressibility, m_v = volume compressibility, C_v = coefficient of consolidation, C_α = secondary consolidation, RC = ratio of compression, CR = compression ratio, k- permeability coefficient.

Parameters	Code/Method	Range	Data retrieved from available literature
C_u- UCS (k Nm^{-2})	IS:2720-12 (1981)	5.4–18.1	3.9 (Long 2005, UK), 12.8 (Latifi *et al.* 2016, Malaysia), 14.2 (Chowdhury *et al.*2016, Bangladesh), 13.9 (Kolay *et al.* 2015, Malaysia), 7.8 (Khalid *et al.* 2013, Malaysia), 8.2 (Rahman *et al.* 2016, Malaysia); 15.4 (Moayedi *et al.*2013, Malaysia), 13.9–21.2 (Animur *et al.*2016, Malaysia), 4.9–9.8 (Hebib *et al.*2003, Ireland)
Cu- TXCU (T m^{-2})	IS:2720-10 (1991)	3.7–14.7	5.7-12.8 (Paul & Hussain.2019, NE India), 5.9–37.3 (Islam *et al.* 2004, Bangladesh), 5.8–15.2 (Anggraini *et al.*2006, Malaysia), 9.0–10.8 (Ulusay *et al.*2010, Turkey), 34.3 (Kazemian *et al.* 2009, Malaysia), 2.9–12.8 (Wong *et al.* 2016, Malaysia)
Ø		1–10°	2–3 (Paul & Hussain 2019, NE India), 12 (Kazemian *et al.* 2009, Malaysia), 16 (Latifi *et al.* 2016, Malaysia), 2–24 (Huat *et al.*2004, Malaysia); 3–25 (Wahab *et al.* 2018, Malaysia)
C_c		0.8–2.1	0.3–0.5 (Islam *et al.*2004, Bangladesh), 1.1–2.4(Ulusay *et al.* 2010, Turkey), 1.7–2.3 (Duraisamy *et al.* 2009, Malaysia), 2.0–2.5 (Santagata *et al.* 2008, USA), 0.5 (Kaniraj *et al.* 2011, Malaysia), 0.8–0.9 (Reddy *et al.* 2014, India), 0.5–2.6 (Nie *et al.* 2012, China)
e		1.2–3.5	1.1–2.0 (Islam *et al.* 2004, Bangladesh), 2.4–11.2 (Badv *et al.* 2012, Italy), 2.4–2.4 (Hashim & Islam 2008, Malaysia), 2.6–3.3 (Ulusay *et al.* 2010, Turkey)
$a_v \times 10^{-4}$ (m^2 kN^{-1})	IS:2720-15 (1965)	16.3–20.6	-
$m_v \times 10^{-4}$ (m^2 kN^{-1})		10.7–13.5	16.0–30.7 (Ulusay *et al.* 2010, Turkey)
$C_v \times 10^{-9}$ (m^2 s^{-1})		0.2–1.6	0.9–2.5 (Nie *et al.* 2012, China), 0.1–0.4 (Wong *et al.* 2008, Malaysia), 0.2–0.4 (Adejumo 2012, Nigeria), 0.2 (Reddy *et al.* 2013, India), 1.5–7.8 (Paul & Hussain 2019, NE India)
$C_\alpha \times 10^{-2}$		3.1–5.9	0.9–52 (Fox *et al.*1992, USA), 1.7 (Fox *et al.*1999, USA), 1.5–2.5 (Ulusay *et al.* 2010, Turkey), 0.3–2.1 (Wong *et al.* 2008, Malaysia); 3.0 (Reddy *et al.* 2014, India), 3.3–9.0 (Ali *et al.*2016, USA), 1.1–1.6 (Adejumo 2012, Nigeria), 2.2–6.7 (Paul & Hussain 2019, NE India), 1.9 (Varghese *et al.* 2019, India)
RC=(C_α/C_c) $\times 10^{-2}$		1.9–2.8	2.0–10.0 (Mesri *et al.*1987, USA), 0.1–4.5 (Fox *et al.*1992, USA), (2.1–7.0 (Fox *et al.*1999, USA), 2.7–3.8 (Duraisamy 2007, Malaysia), 1.5–2.0 (Paul *et al.*2019, NE India), 2.1–3.3 (Varghese *et al.* 2019, India)
CR=($C_c/(1+e_o)$)		0.4–0.5	0.4–0.5 (Hebib *et al.*2003, Ireland), 0.3–0.5 (Huat *et al.*2004, Malaysia), 0.4–0.5 (Paul & Hussain 2019, NE India)
$k \times 10^{-11}$ (cm s^{-1})	-	2.1–2.7	1.5–3.7 (Paul & Hussain 2019, NE India), 6.7 (Santgata *et al.* 2008, USA), 0.1–6.2 (Reddy *et al.*2013, India)