Engineering properties of peat in estuarine environment

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ABSTRACT: The objective of this study is to carry out an in-depth study of the engineering properties of peat soil in estuarine environments in selected countries. These countries are: Australia, Ireland, Italy, Malaysia, Netherlands, Turkey, and Vietnam. Peat is highly organic, extremely compressible and is known to be problematic for geotechnical works. Peat exhibits unique geotechnical properties in comparison with those of inorganic soils such as sandy, silty or clayey soils. It has an adverse effect on the settlement of foundations where the highly compressible peat can bring about excessive settlements for buildings constructed above it. Further, peat causes instability problems such as development of slip failure, local sinking, and massive primary and long-term settlement even when load increases moderately. This paper reviews and investigates the engineering properties of peat soil in those countries with reference to the physical and geotechnical properties.These properties are:consolidation characteristics, Atterberg limits, density, organic content, shear strength, and moisture content. Moisture content and organic content are the most indicative characteristics of peat due to its extraordinary high moisture and organic content. Surfers Paradise South East Queensland has been selected as the study area for peat in Australia for examining the engineering properties of peat. Peat in this region is embedded at depth ranging between 1.10 to 40.90 m below the ground surface and hasthickness reaching 7 m in some locations. A comparison between peat in Surfers Paradise and the aforementioned countries is also provided. Finally, the behaviours of peat in studied area are assessed and conclusions are made.

Keywords: Peat, Atterberg Limits, Consolidation, moisture content, organic content, foundations

1 Introduction

The term peat denotes soils with high organic content derived mainly from plant remains. It has spongy consistency, dark brown to black colour, and organic odour (Figure 1). Remains of plant fibres occasionally are visible but they may not be recognisable in the progressive process of decomposition. Peat is an accumulation of disintegrated plant remnantswhich have been preserved under condition of high water content and incomplete aeration (Huat 2004). Peat also can be defined as "generally unconsolidated organic material consisting largely of organic residues accumulated as result of incomplete decomposition of dead plant constituents under conditions of excessive moisture" (Landva 2007). Irrespective to the geographic location, peat accumulates wherever conditions are suitable, which is, in area with surplus rainfall and poorly drained ground (Huat 2004). Andriesse (1988) stated that the formation of the organic materials is a result of the biochemical process. However, the accumulation process depends on the ecosystem and climate conditions. Peat has no precise definition between soil scientists and engineers. Soil scientists have defined peat as a soil with organic content greater than 35% however; geotechnical engineers define the peat as soil with organic content greater than 20% (Huat 2004). According to Radforth (1969) peat can be divided into three main types for engineering purposes. First, amorphous – granular peats which have high colloidal minerals and seem to be like clay in grain structure where the inter-spaces water is kept

locked in an adsorbed condition around particles. The two peat types are fine-fibrous and coarse-fibrous peats which hold the inter spaces water in the peat mass as a free water and these types are described as woodier peat.
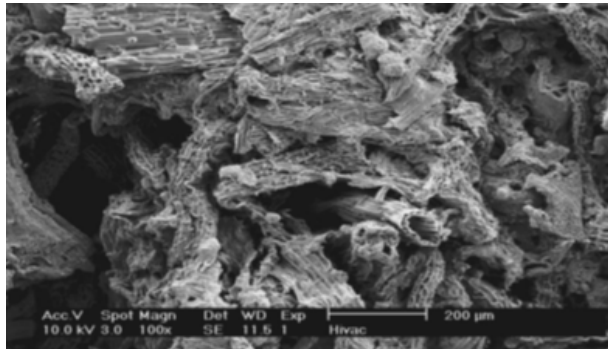

Figure 1 Microphotograph of peat
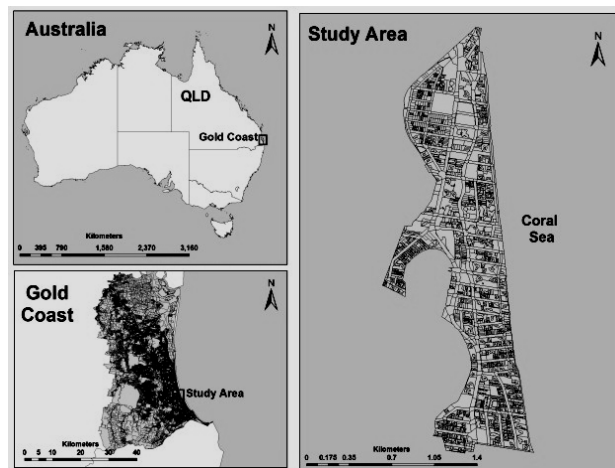(Mesri and Ajlouni 2007).

Figure 2. Location of the study area
in the Surfers Paradise, Australia.

It is generally accepted that the organic matter present in soils causes a detriment of their geotechnical and engineering qualities (Malkawi et al. 1999). Manyengineers consider peats as problematic soil because of their abnormal properties. These soils, according to Kazemian et al. (2011) are geotechnically problematic and cause instability problems such as development of slip failure, local sinking, and massive primary and long term settlement even when load increases moderately, because of their low shear strength and high compressibility.Therefore, these soils are very unsuitable for construction because they cannot support the foundations.

The development of the infrastructure of a country is an indication for economic prosperity. Therefore, the contribution of geotechnical engineeringcannot be overemphasized. Consequently,

this paper reviews and investigates the engineering properties of peat in selected countries. These countries are: Australia, Ireland, Italy, Malaysia, Netherlands, Turkey, and Vietnam.

2 Peat Occurrence in estuarine environment

2.1 Peat layer in Surfers Paradise, Australia

Surfers Paradise is a business and tourism hub of Gold Coast, South East of the state of Queensland, Australia. It has been an iconic tourist destination since 1950s and considered as the most famous place throughout Australia. Figure 2 shows the geographic location of the study area. The Surfers Paradise has an area about 4 by 1.3 km^2. The reduced level used in this paper is based on the Australian Height Datum (AHD). The subsoil profile of the Surfers Paradise consists of loose to medium dense sand from the ground surface until R.L. 2.3 m. Then a layer of medium dense sand to dense sand between R.L. 2.3 to -3.2 m is encountered. After that a layer of very dense sand is occurred between R.L. -3.2 to -20 m.Within the very dense sand layer, varying thickness peat layer is occurred at depth between (R.L. -10 to R.L. -19.6 m) at different locations with thickness ranging from (0.1 – 7 m). Inter-bedded firm to very stiff clay layers are found up to (R.L. -26.6 m) where a layer of firm to hard clay is occurred below it until the depth (R.L. -29 m). The last layer of this soil profile varies within the study area where in some locations an inter-bedded layer of medium dense sand, gravelly sand, clayey sand, sandy clay, or hard silty clay can be observed.This subsoil profile is consistent with the description given by Oh et al. (2008).

According to Whitlow (2000), peat deposits have occurred on the Gold Coast region (where the study area is located) due to current and past marine processes near coastal zones. These marine deposits have been laid down ten thousand years ago or during the Holocene geological period. Peat deposits which are found at 26.8m in depth have been aged at 10,585 ± 140 years predating present by using radiocarbon method (Thom and Chappell 1975). Obviously, peat deposits can be seen inthree main types within the marine deposits: coastal swamp deposits which comprise of quartz sand and peaty quartz sand, dune lakes deposits which contain sand and organic deposits, and beach swale deposits which include peat deposits overlying quartz sand (Whitlow 2000).The physical and engineering properties of peat in Surfers Paradise have been presented in Table 1.

Table 1 Geotechnical parameters of peat in Surfers Paradise.

| Parameter	Values	Parameter	Value
Liquid Limit	259-305 %	Coeff. of Secondary Consolidation (Cα)	0.03-0.04
Plastic Limit	125 – 207 %	Over Consolidation Ratio (OCR)	1.1 – 2.8 %
Plasticity Index	88 –134	Apparent Cohesion	43-166 kPa
Water Content	168 – 247 %	Apparent Friction Angle	0–14 Degree
Unit weight	1.14 t/m^3	Shear Strength	30–40 kPa
Coeff. of Consolidation (Cv)	1.12 – 40.5 m^2/year	Ash Content	20%
		Specific Gravity	1.572
Coeff. of Volume Compressibility (Mv)	7.00E-05–1.30E-04 m^2/kN	Permeability (k)	1.40E-05–2.40E-07 m/sec
Compression Index (Cc)	1.83-2.74	Organic Content (estimated)	63-68 %
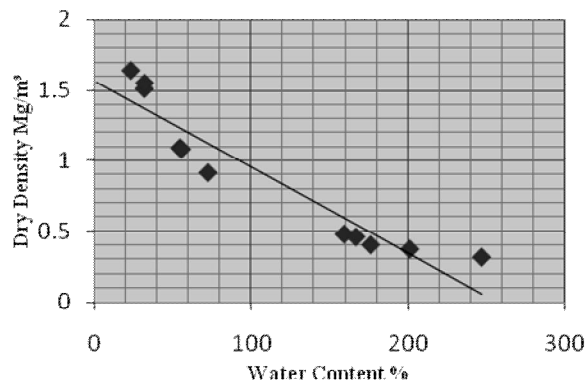
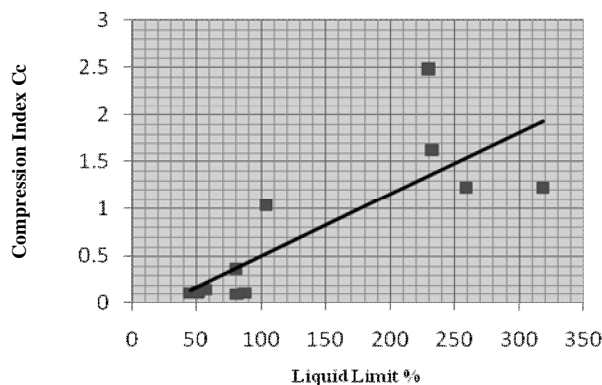Figure 3. Water content versus dry density in Surfers Paradise

Figure 4. Liquid limit and compression index correlation in Surfers Paradise.

It can been seen from these properties that peat in Surfers Paradise has low shear strength (30-40 kPa) and high moisture content (up to 247%). Organic content has been estimated to be 63-68 %. The Standard Penetration Test (SPT) *N* values range between 0-19. The high value of SPT-N in the peat could be attributed by occurrence of fibres within the peat structure.Further, dry density of Surfers Paradise peat decreases with the increase of water content (Figure 3) and the empirical formula of this relationship is given in Eq. (1).

$$Dry\ Density = -\,0.0061w + 1.5635 \qquad (1)$$

where w= Water content

Furthermore, an empirical formula has been established between the compression index and liquid limit (Figure 4). This formula shows an increase in the compression index with the increase of liquid limit (Eq. (2)):

$$Cc = 0.0066LL - 0.1603 \qquad (2)$$

where Cc is the compression index and the LL is the liquid limit.

2.2 Peat Occurrence in Ireland

Peat failures are familiar to happen throughout the world especially in British Isles where 80% of reported failures have occurred (Dykes and Kirk 2006).The historical record of peat failure in British showed that there were more than 70 failures during the last 400 years (Figure 5) and a remarkable increase starting from 1800 till now (Boylan et al. 2008). Due to intensive rainfall, peat landslides have been triggered towards the later years of 1900s. In Pollatomish in Ireland 11 peat landslides have been occurred in 2003 within the peat mass.

The estimated number of fatalities was 36 over the period 1600 to the present which equal to 0.1 victims per year. The interesting fact in this type of failure is the mobility of peat failure which travels

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long distance from the failure source. For instance, in Knockmageeha city in Ireland the failure extended to 15 kilometres from its source in 1896, when the peat debris rapidly broke down into slurry and flowed within the drainage system as a viscous fluid which increased the risk of its movement.
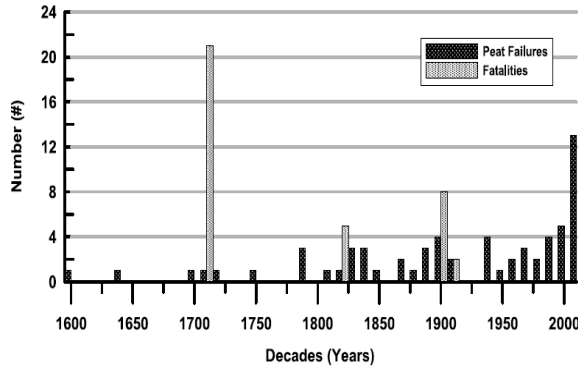

Figure 5. Number of peat failures and fatalities in Ireland from 1600 to present (Boylan et al. 2008).

Boylan et al. (2008) have performed a study on the issues surrounding peat slope failure in Ireland to be of interest to engineer or engineering geologist assessing this geohazard. They stated that peat formation started in Ireland following the end of the Ice Age, some 10 000 years BP.It can be observed that moisture contents ranged from 800% to 1300% where, the moisture content decreases with increasing humification (Hobbs 1986). Linear shrinkage values from the study site decrease from close to 50% at 0.75 m to about 40% at 2 m depth, possibly reflecting the reduction in fibre content with depth. The bulk density of this site was 1.03 Mg/m^3. Boylan et al. (2008) stated that there is a general tendency of increasing peat thickness with reduction in slope angle. Further, they found that the majority of the failures are clustered between 4° and 8°. This may correspond to the slope angles that allow a significant amount of peat to develop that over time becomes potentially unstable.

2.3 Peat Occurrence in Italy

The geotechnical properties of some Holocene alluvial deposits have been identified by Campolunghi et al. (2006) in the city of Rome. This city in Italy has a long term of human activity and the original terrains have been continuously changed into an urban area. In Rome's historical centre, it becomes very difficult to recognise the original terrains due to the modification of Tiber's right and left banks. Historically, this modification took place more than once and it has sometimes been effaced by constructions and urban growth (Capelli 1999).

The right bank of Tiber River which hosts the Vatican, Monte Mario and Gianicolo don't havegeotechnical problems. That is because it mainly comprises of sand, silts and gravels (as coarse grains on average) as well as entirely lacked in an organic content. Therefore, the geotechnical properties are typically considered as consolidated soils with medium deformability (Campolunghi et al. 2006). The left bank soils, in contrast, are described as fine grained deposits with abundance of silts and clays. Organic content and peat, which do not exist in the right bank, were found in the left bank deposits (Figure 6). Fosso di GrottaPerfetta which is one of the Tiber River tributaries comprises of up to 20% of organic-rich units and on range about 5m thick (Campolunghi et al. 2006).

The difference between the right and left bank deposits reflects the variation in the geotechnical parameters and soil behaviour. Malkawi et al. (1999) stated that the organic content in clays is the main cause of its deformability and low-strength. This was confirmed by Campolunghi et al. (2006) when they measured the geotechnical parameters for the left bank deposits (see Table 2) which display a low shear resistance values with high levels of deformability in organic rich layers which are found in the alluvial deposits within the city of Rome. Monge et al. (1998) said that the structure of organic rich deposits is more sensitive.
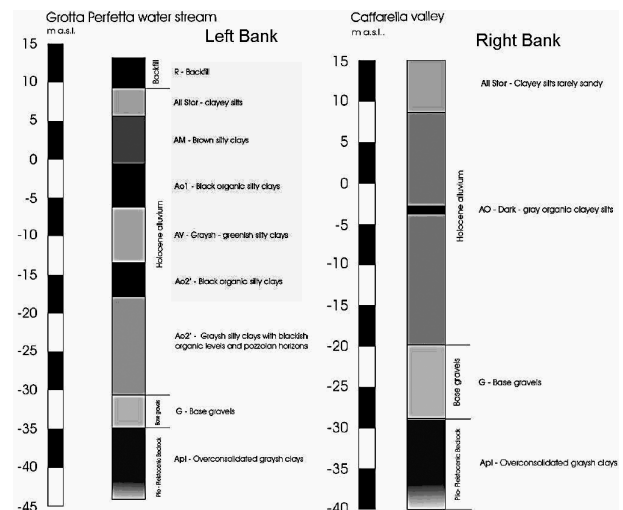

Figure 6. Representative series referred to the left and right banks of Tiber River in Italy (Campolunghi et al. 2006)

Table 2. Geotechnical parameters of the lithotechnical units identified in GrottaPerfetta (Left Bank) deposits (Campolunghi et al. 2006).

Units		Average thickness (m)	γn (kN/m3)	WC %	LL%	IP %	φ′	C′ (kPa)	Cu (kPa)
Hist. All	Historical floods	3	16-19	32-65	//-78	NP-23	30-47	0-38	_
AM	Brown clays	7	15-19	30-93	43-123	17-58	23-30	5-35	21-74
AO1	Organic clays	6	12-15	91-186	102-171	33-93	13-22	9-25	16-55
AV	Green clays	8	12-17	49-154	84-151	24-79	17-29	3-15	7-19
AO2′	Organic clays	5	14-16	42-184	63-164	18-76	13-26	5-25	15-33
AO2·	Organic clays	15	16-19	28-84	46-104	17-65	25-30	0-0.3	15-30

// indicates no data.

The alluvial sediments in Tiber Riverare subject to seismic amplification andthe structure of organic-rich units are more 'sensitive'(Monge et al., 1998). Such sediments are mostly under-consolidated,hence, more subjected to settlement. Through data derivedfrom some alluvial deposits in the City of Rome (includingthose of the Tiber), it is possible to identify areaspotentially at risk from instabilities caused by the presence of organic matter (Campolunghi et al. 2006).

2.4 Peat Occurrence in Malaysia

Malaysia has peat deposits observed predominantly along the coastal area (Figure 7) except in Sri Aman (Zainorabidin and Wijeyesekera 2007).

Figure 7. Location of peat swamps in Malaysia (modified from Mutalib et al.1991).

These deposits occur at varying depths between 1-20 m (Huat 2004). The annual rate of peaty soil's subsidence was predicted as 2 cm per year(Wösten et al. 1997). Concerns surround this subsidence especially when acid sulphate soils which occur frequently underneath the peat, might surface. For more temperate regions, this subsidence rate was high for Malaysia compared with the rates in Netherlands where the subsidence rate was the lowest with relation with ground water levels. The rates of subsidence in Indiana and FloridaState were higher than those in the Netherlands (Figure 8).
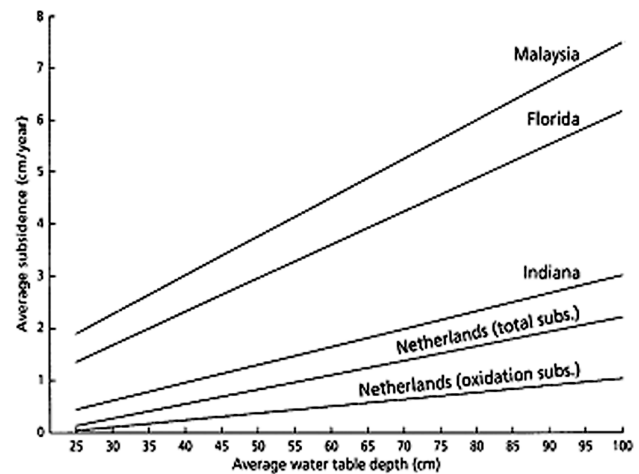

Figure 8. Subsidence rate versus groundwater level relationships for different areas in the world (Wösten et al. 1997).

In Indiana the subsidence rate was approximately 0.5 cm a year, in contrast,the rate in Florida was some 1.4 cm a year (Wösten et al. 1997).

The result of the study in Malaysia shows that 60% of subsidence could be attributed to the oxidation and 40% to the peat shrinkage. Al-Raziqi et al. (2003) have performed laboratory shear box tests in different locations in Malaysia. The result as presented in Table 3, showed that cohesion values are between 6-17 kPa and the friction angle is between 3-25°. Huat (2004) stated that with the occurrence of more fibres in peat, the friction angle becomes higher. Also, shear strength parameters are lower with increasing degrees of humification (less fibrous).

Table 3 Laboratory shear box test results of peat in different locations in Malaysia (Al-Raziqi et al. 2003).

Location	MC	OC	LL	Von Post Scale	C (kPa)	φ
Banting, Selangor	211	85	294	H1	9-11	9-20
	195	79	219	H2	6-11	9-16
	832	84	361	H5	8-10	7-10
	219	94	316	H6	11-12	9-12
	225	85	166	H8	8-12	6-11
Kg. Jawa, Selangor	215	78	180	H3	10-12	6-14
	209	89	325	H6	12-14	7-25
	786	85	368	H8	7-11	8-13
Kg. Jawa, Selangor	680	85	298	H3	11-12	10-15
	747	93	352	H5	10-12	5-10
	720	83	282	H7	7-9	9-12
Dengkil, N. Sembilan	246	98	305	H2	13-17	3-12
	301	98	335	H5	11	13-15
	786	83	377	H8	8-9	12-20

Because Malaysia aspires to achieve a status of developed country by 2020, escalating andfast infrastructure construction movement has been adopted. Based upon that, a lot of projectsare being erected on soft soils such as marine, organic and peaty soils because of lack ofgood conditions ground.

A good example of these projects is a Kuala Lumpur InternationalAirport (Zainorabidin and Wijeyesekera 2007). Peat in Malaysia is categorised as a tropicalpeat (Anderiesse 1988) and occurs along the coastal areas especially in Sarawak where 16,500 km^2 of its land is covered by dark reddish brown to black peat (about 89% of Sarawak's area) (Zainorabidin and Wijeyesekera 2007).

Peat problems and variety of settlement rates have been emerged in Malaysia.According to Zainorabidin and Wijeyesekera(2007), serious diagonal fissures and cracksobserved near windows, doors, and the opening of the houses even during the process ofconstruction. Moreover, the settlement rate surpasses 300 mm in the first year of construction. Also, differential settlement observed exceeds 1:150 for the majority of buildings. The predicted settlement was 1440 mm for 3 months with 3 m surcharge and 2800 mm for 6 months.

Further, Abdullah et al. (2007) and Hashim and Islam (2008) have performed a study on the peat in Sessang and Klang peat in Malaysia respectively. Researches accomplished efforts to characterise and stabilise the peat in Malaysia due to its wide occurrence as well as frequent subsidence and settlement problems.

2.5 Peat Occurrence in the Netherlands

In The Netherlands, the polder surface layers comprise soft organic clay and peat which are pressed upwards due to the high potential head from the river. Therefore, the passive resistance of the inner slope will be reduced through the underlying sand layers. The delicateness of the peat and organic soils is problematic in tunnels construction when the tunnel cannot find underlying hard layers to settle (Haan and Kruse 2007).

Figure 9. Wilnis dyke the morning after (Haan and Kruse 2007).

Table 4. Properties of basal peat layer, Wilnis canal dyke (Haan and Kruse 2007).

Bore No	Depth (m)	ρ (t/m^3)	w_0 %	σ_p (kPa)	Estimated e_0	Estimated σ_p (kPa)	σ_v (kPa)
Oost-2-04	1.67	0.97	379	15	12.5	17	18.5
Oost-2-03	2.77	1.03	624	31	10	30	31
Oost-3-3BA	3.8	1.01	511	40	8.5	45	42.5
Oost-3-2BA	4.75	1.04	455	50	8	53	54
Oost-3-1BA	6.8	1.05	450	68	7.8	56	71

A canal dyke in Wilnis city in the Netherlands which comprises of peat soil has failed in August 2003. This failure caused a partially an inundating of the downstream polder (Figure 9). Dyke's body is represented by organic clay layers and soft peat which deposit on the Pleistocene sand. The geotechnical parameters of peat are presented in Table 4. In the past, failure occurred as a result of decomposition and weathering of the peat as well as, heavy rainfall after a long period of drought (Haan and Kruse 2007).

In 2003, during the dry summer, the evapotranspiration caused a weight reduction and affected the marginal uplift stability of the dyke's toe at the downstream slope. Gaps occurred and enhanced along the wooden sheet pile due to lateral movement and shrinkage of the crest of the duke. Therefore, hydraulic fractures occurred from the beginning of the wooden sheet pile to the underlying layer of sand.

The dyke failed by lateral displacement because of the loss of shear resistance along the base of the peat and soft layers. That is because of increasing uplifting pressure from the canal mainly because a silty/loamy layer lies under the dyke materials and enabled the hydraulic pressure to be directed under the dyke body (Figure 10).
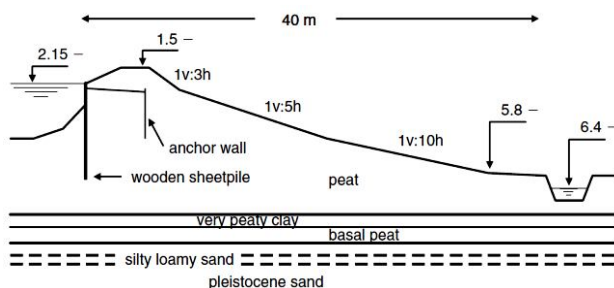

Fig 10. Cross section of the Wilnis dyke (Haan and Kruse 2007).

This dyke laterally displaced between 5-8m and 60cm in length along the dyke section. Other possible factors and causes contributed in this failure such as gas occurrence in the peaty base and Pleis-

tocene sand which reduced the bulk density of those layers. Visually, gas was detected underneath by CPT camera sounding as an undissolved gas in the pores of the peaty soil. These pores are formed by the decomposition of the peat. Materials in the underlying layers could be compacted and consolidated due to gas pressure causing in the higher yield stress, higher shear strength and reducing water content (Haan and Kruse 2007).

Hoogland et al. (2011) computes the subsidence rate of peaty and non-peaty soils in the eastern area of Amsterdam, Utrecht, Rotterdam and Den Haag in the Netherlands. They found that the predicted cumulative subsidence rate between 2005 and 2020 was over 80 mm. On the contrary, this rate was 10 mm (over these 15 years) when peat is absent or thin in soil profile (Figure11). This subsidence took place due to sea level rising and tectonic subsidence of the western parts of the Netherlands (Kooi et al. 1998). Sea level rise due to climate change accelerates land subsidence through peat oxidation process (Remkes et al. 2007).
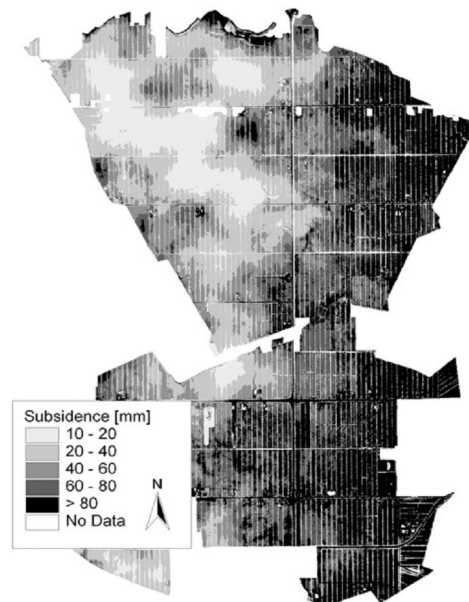

Figure 11. Forecasted subsidences between 2005 and 2020 in the Netherlands (Hoogland et al. 2011).
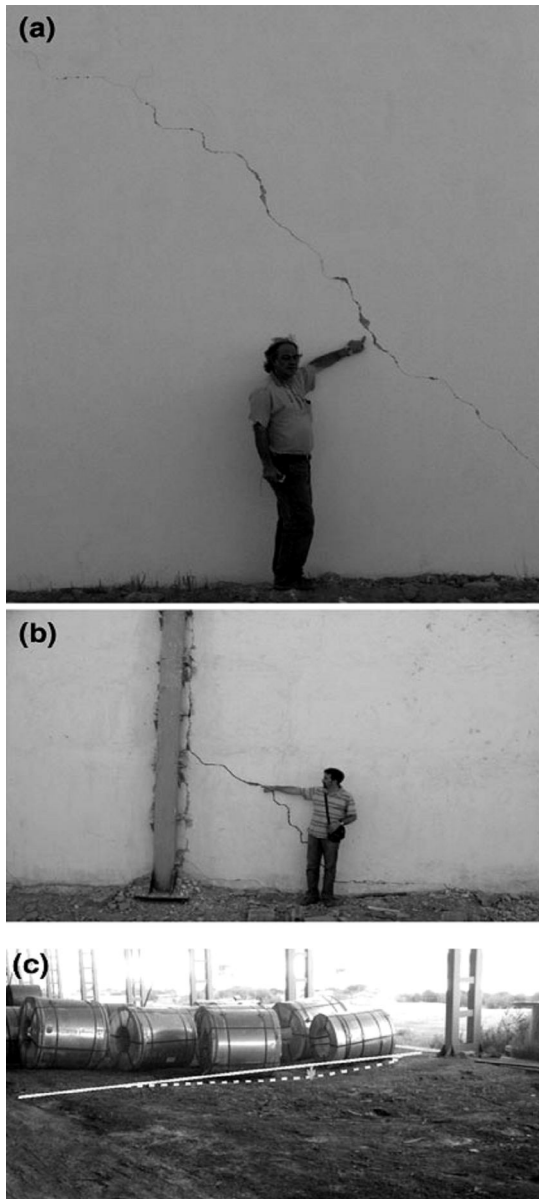
Figure 12. (a) & (b) Settlement cracks observed on the walls of some structures, and (c) settlement of heavy rolls of metal wires (bobbins) put directly onto the peat (Ulusay et al. 2010).

2.6 Peat Occurrence in Turkey

Ulusay et al. (2010) stated that a huge industrial zone in Turkey called (KOID) (Kayseri 1st Organised Industrial District) is suffering from cracks on the walls of structures as well as deformations of the surface ground. These structures are large and heavy metal framed buildings (Figure 12). This industrial zone extends over approximately 2,400 ha and was established in 1976. Now, KOID considers as the largest and well developed organised industrial zone in Kayseri city, central Anatolia in Turkey. This problem extends to the adjacent structures in the Kayseri Free Trade zone (KAYSER) which is established in 1998 on 690 ha over peat deposits. Sert and Onalp (2007) have done a geotechnical study on the peat for the same area in 2007 when settlement of a rigid platform was took place on the peat. Turkey has a 56,000 ha of peat lands (Ulusay et al. 2010).Peat thickness in this site in 22 boreholes was between 0 - 7.5 m and it was confirmed by satellite images (Ulusay et al. 2010), where other types of peat layers were found between 20 - 220 m as a lignite (intermediate state between coal and peat) and Gyttja (a mud rich in organic matters found at the bottom or near shore or certain lakes).

SPT- N values were between 3 - 4 blows, peat's colour was dark brown to black, the soil was easily squeezed by hand, recognisable plant remnants, and water saturated. The natural water content was between 118 - 211% at the top, while it ranges between 105 - 559% for the peat from the boreholes. Other geotechnical properties for peat layers in Turkey fall within the ranges for peats from other countries (Ulusay et al. 2010). The peat near the surface lies between H3 and H4 class (Table 5), but when depth increases it lays between H5 and H7 according to Von Post scale of humification.

Table 5. Physical and index properties of the peats in Turkey (Ulusay et al. 2010).

Borehole No.	Depth (m)	Degree of Humification	W%	γ_b (kN/m^3)	γ_d (kN/m^3)	e	G_s	LL (%)
AC1	0.7-1.9	H3-H4	181.2	10.5	3.41	4.68	1.73	315.1
AC2	0.7-2	H3-H4	135.8	11.4	4.49	3.35	2.13	-
SK1	4.5-8.45	H5-H7	239.3	12.27	4.59	2.98	2.06	260.3
SK2	0.5-6.95	H5-H7	322.6	13.8	6.26	2.19	1.98	147.5

2.7 Peat O2.4 Peat Occurrence in

Vietnam is located in the centre of Southeast Asia, and it lies in the eastern part of the Indochina peninsula. The country is crisscrossed by thousands of streams. The main rivers are Red River (north) and the Mekong River (south). Both rivers are in the Mekong Delta. The peat lands dominate and occur over approximately 12,000 ha (Anon. 2013). Deltas contain thick peat deposits and soft soils which

must necessitate special strategies (Rau 1994). Peat in Mekong Delta (see Figure 13) has been dated by using radiocarbon method in Tanan as 2700±120 years BP (Nguyen et al. 2000).

Figure 13. Decomposed peat sample in Vietnam (Quoi 2010).

Mekong Delta is one of the largest deltas in Asia and is occupied by eleven provinces (Nguyen et al. 2000). The estimated population in this delta is 17 million (Buschmann et al. 2008) and the peat area is 341 km^2 (Quang 2009). Table 6 shows the distribution of peat in Vietnam.

Table 6 Recorded peatlands in Vietnam (Anon. 2013)

Locations		Reserves	
Provinces	Districts	Area (ha)	Million tons
Lang Son	Binh Gia, Na No	7	0,3
BacNinh	Yen Phong	5	0.06 – 0.2
Ha Nam	Ba Sao, Kim Bang, Tam Chuc	31	7.3
NinhBinh	Gia Son, Son Ha	13	2.0
Quang Tri	GioLinh	6	0,15
TT – Hue	PhongDien	31	1.5 – 2.0
BinhDinh	My Thang	9	-
DakLak	Cu M'Gar	7	-
Lam Dong	BaoLoc, Di Linh	12	-
Dong Nai	Long Thanh	30	0.4
Tay Ninh	Trang Bang	25	0.4
Long An	Duc Hue, T.Hoa, T. Thanh	72	-
TienGiang	Tan Phuoc	21	-
Ben Tre	BinhĐại	17	-
An Giang	Tri Ton	62	16.4
KienGiang	An Minh	2,900	-
Ca Mau	T. V. Thoi,	7,531	14.0

(-) recorded but not inventory

Geological perspective on land comprises hard formations (intrusive and extrusive rocks) which are of high bearing capacity and high resistance to hazards. Unconsolidated formations (Quaternary and Neogene formations) are of low to moderate bearing capacity and resistance to hazards (Nhuan et al. 2008). The Major soil groups are shown in Figure 14.
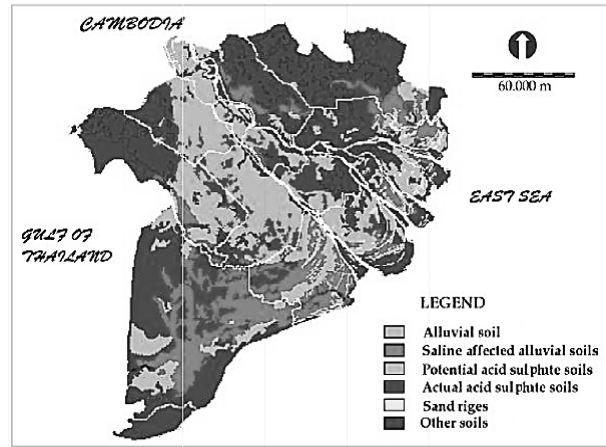

Figure 14. Major soil groups in Mekong Delta (Quang 2009).

Biggs (2011) stated that during most of the colonial periods, the government mainly considered plans to excavate the peat and clear the land. In the Mekong Delta region, the underneath of peat layer is mainly marine swamp sediment which contains sulphide materials. If this sediment oxidised, it will produce a high amount of acidity to the peat (Quoi 2010). It is estimated that the sea level will rise 0.2-0.4 m during the next 50 years (Nhuan et al. 2008). That, will trigger the problems of peat oxidation and acid sulphate soil.

Due to the destructive fires in 2000 and 2002 in Mekong region, canal systems have been built for fire control purposes. According to Quoi (2010), these systems have resulted in subsidence of the peat due to increased loss of water in the dry season and bring the bulk density to about 0.23 t/m^3. Also, the unnaturally maintained high water level and flooded peat areas for most of the year has led to increase peat moisture content and increase of the decomposition dynamic (Vien et al. 2010). Decomposition of peat leads to increase the humification and reduce fibres content, in turn, to increase shear strength and reduce compressibility.

Mekong River Delta has been investigated by Dornbush et al. (1969) for depositional environments purposes in the context of engineering constructions. This study has been done on a limited

area along the national road number 4 to examine the soil suitability for foundations. Buschmann et al. (2008) stated that subsurface sediments have not been previously researched in details. They said that in Plain of Reeds and Longxuyen Quadrangle there is peat of 2-5 m deep, 100-300 m wide and 500-2000 m long. Also, Chiem (1993) stated that a very dark brown peat layer at 40-45 m in Mekong Delta. From his profile it can be understood that the peat layer occurs up to 45 m in depth and below it there is non-organic silty clay.

Peat layer in Vietnam and particularly in Hanoi are very abundant and often over 10 m thick and land subsidence of more than 20 mm/year has been reported for many years in this area (Berg et al. 2001). Thu and Fredlund (2000) have studied the land subsidence due to the groundwater pumping in Hanoi city. They stated that there are serious settlement problems and signs of distress on some of the building as a result of ground surface settlement. Areas experiencing ground settlement are underlain by highly compressible deposits. This validates the occurrence of 10 m thick of peat layer in Hanoi stratigraphic profile. Thu and Fredlund (2000) stated that their study is limited to the compilation and analysis of the existing data due to the difficulties in obtaining the relevant data. Further, they acknowledge that the subsidence rate is about 20-35 mm/year in areas where the soil strata are consisting of peat and organic materials.

3   Concluding remarks

A review of the peat properties, as well as the previous research performed has been carried out. This study shows that peat soils in different regions of the world exhibit markedly different physical and engineering properties. High compressibility, low shear strength, and high moisture content are the main characteristics which define the peat ubiquitously. Further, this review has shown laboratory and field measurement of peat properties to be taken into account by geotechnical engineers.

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