MAPPING AND MODELLING OF PETROPHYSICAL AND STRATIGRAPHIC PROPERTIES OF PEAT SOIL WITH GROUND PENETRATING RADAR

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ABSTRACT

Peatland's economic importance and environmental impact have made it attractive to scientific research. Great amount of works were done in studying its petrophysical behaviours. Most of the works are however done with reference to the peatland deposit of the temperate and cold belt region of the Northern Hemisphere. The complex behavior of petrophysical properties of peat soil especially in relation to changes in climatic conditions necessitates the need for extensive research toward understanding the behavior of these properties in relation to tropical climate. In this work, field survey data acquired with ground penetrating radar and laboratory analysis of core samples collected were used to model Ground Penetrating Radar (GPR) data with moisture content for the purpose of developing empirical relationship between the two parameters. A third-order polynomial relation was found to be the best fitting model (R^2=0.9657, N=36, P <0.001) with a standard error of 0.0124. The model was used to map the spatial distribution of moisture content of the study area. A texture extraction technique was used to map the biogenic gas content of the deposit based on the effect of the gas on radar image texture and signal parameters. Three regions of high gas concentration were identified with a maximum content of 19.57% recorded at the northwest end of the study area. The regions are therefore considered as forest fire hotspot. Stratigraphic sequences of the peat deposit were also delineated based on signal reflection boundaries. Three major stratigraphic layers were identified and analyzed with core samples. The layers and their mean ash contents are experimentally found to be: Fibric (33.34%) at 0.3-1.2 m depth range, Hemic (3.74%) at 1.2 - 2.6 m depth range and kaolinite clay (20.27%) at 1.7-2.5 m depth range. The work provides bases for the survey of tropical peatland with GPR.

ABSTRAK

Kepentingan ekonomi terhadap tanah gambut dan impaknya kepada alam sekitar telah membina daya tarikan tersendiri bagi penyelidikan saintifik. Kebanyakan kerja-kerja telah dilakukan terhadap sifat petro-fizikal tanah gambut dengan merujuk kepada kandungan tanah gambut dari lingkaran kawasan sederhana dan sejuk di Hemisfera Utara. Ciri-ciri kompleks dalam sifat petro-fizikal tanah gambut ini berhubung dengan perubahan keadaan iklim memerlukan suatu tindakan penyelidikan yang meluas ke arah memahami hubungannya dengan iklim tropika. Dalam kajian ini, data kajian lapangan diperolehi dari tanah gambut Pontian menggunakan Ground Penetrating Radar (GPR) manakala analisis makmal dilakukan terhadap sampel utama untuk angkatap model dielectric yang didapati dari data GPR dengan kandungan lembapan bertujuan membangunkan hubungan empirikal antara dua parameter. Polynomial darjah ketiga memenuhi kehendak menjadi model terbaik (R^2 = 0.9657, N = 36, P <0.001) bersesuaian dengan ralat piawai 0.0124. Model ini telah digunakan untuk memeta taburan spatial kandungan kelembapan kawasan tersebut. Satu teknik pengekstrakan tekstur telah digunakan untuk memetakan kandungan gas biogenik tanah tersebut berdasarkan kesan gas terhadap tekstur imej radar dan parameter isyarat. Tiga kawasan yang telah dikenal pasti dengan kepekatan maksimum kandungan gas yang tinggi 19.57% direkodkan pada kawasan barat laut dikawasan kajian ini yang dianggap boleh berlakunya kebakaran hutan. Berdasarkan refleksi isyarat lapisan sempadan tanah gambut, tiga lapisan urutan stratigrafik utama telah dikenal pasti dan dianalisis dengan sampel utama. Lapisan diujikaji mendapati purata kandungan abu Fibric (33.34%) pada tahap kedalaman 0.3 hingga 1.2 m, Hemic (3.74%) pada tahap kedalaman 2.1 hingga 2.6 m dan tanah liat Kaolinit (20.27%) pada tahap kedalaman 1.7 hingga 2.5 m. Kajian ini menunjukkan kerja ini dapat menyediakan asas-asas bagi kajian tanah gambut tropika dengan menggunakan GPR.

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LIST OF SYMBOLS

ε	Dielectric permittivity
ε_0	Dielectric permittivity of free space
ε_r	Relative dielectric permittivity
θ	Water content
ρ_b	Bulk density of soil
ρ_p	Particle density of soil
σ	Electrical conductivity
φ	Porosity
AC	Soil ash content
$a_i(n)$	Scan of ith raw data
$a'_i(n)$	Scan of ith processed data
$\vec{B}$	Magnetic induction
c	Velocity of electromagnetic wave in free space
C_{er}	Error in capacitance of a capacitor
C_s	Capacitance of a capacitor with material s as dielectric
C_0	Capacitance of a free space capacitor
f	Signal frequency in Hz
f_c	Central frequency
$g(t)$	Gain function
M_d	Mass of dried soil sample
M_p	Mass of pycnometer
M_s	Mass of as- received soil sample
OC	Soil organic content
v	Radar signal velocity

V_C	Electric potential across a capacitor
X_c	Reactance of a capacitor

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
A C	Aalternating Current
ASEAN	Asssociation of Southeas Asian Nations
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Measurement
CEC	Cation Exchange Capacity
CIFOR	Centre for International Forestry Research
CRIM	Complex Refrective Index Model
EM	Electromagnetic
FAO	Food and Agriculture Organization
f-k,	Frequency –Wave number
GPR	Ground Penetrating Radar
H1-H10	Level of decomposition of peat from list decomposed (H1) to most decomposed (H10)
HYMENET	Hygrometric Measurement Network
IDS	Ingegneria Dei Sistemi, a brand name for GPR equipment manufacture
MS	Mean Squared
NRMSE	Normalized Root Mean Squared Error
RMSN	Root Means Square Noise
SNR	Signal to Noise Ratio
SS	Sum of Squared
TDR	Time Domain Reflectometry
UNEP	United Nations Environmental programme
UNESCO	United Nations Educational, Scientific and Cultural organization

CHAPTER 1

INTRODUCTION

1.1 Background

The vegetation of forest wetland under waterlog and moderate topographic conditions is continuously being decomposed due to series of chemical changes thereby transforming the forest soil structure through fossilization and sedimentation at different rate on different locations. This enhances the heterogeneity and biodiversity of the soil resources. The transformation plays a key role in climate regulation, biodiversity conservation and support for human welfare. Prominent product of this ecosystem transformation is the formation and accumulation of peat soil.

Peat is described as the accumulation of partly decomposed remains of dead plants under waterlogged conditions for thousands of years (Huat, et al, 2009). The formation of peat is as a result of gradual accumulation and decaying of the dead plant materials mostly in marshy areas. These include various types and parts of plant vegetation such as trees, grasses, fungi and their respective parts such as stems, leaves, roots etc. The gradual processes of decomposition lead to the variation in both physical and chemical structure under anaerobic conditions leading to an ecosystem with excessive production of organic matter. Peat can ordinarily be described as organic soil but the continuous accumulation and decomposition of the organic materials leads to the development of a system where the production and accumulation rate of the organic constituents exceed the decomposition rate. This is as a result of the continuous processes of production, death and deposition of plant materials within the forest. Thus peat soil is characterized with excessively higherproportion of organic matter.

Peat is naturally composed of four major components: water, organic matter, mineral matter and gas (Xuehui and Jinming, 2009). Peat contains excessive high water content which ranges from 60% to 90% by mass (Figure 1.1). It could however be as high as 150% to 700% as observed in West Malaysian peat deposit (Huat et al., 2009). The water content of the peat can be chemically or physically bound to the solid component or appears as permeable or free-space pore water.

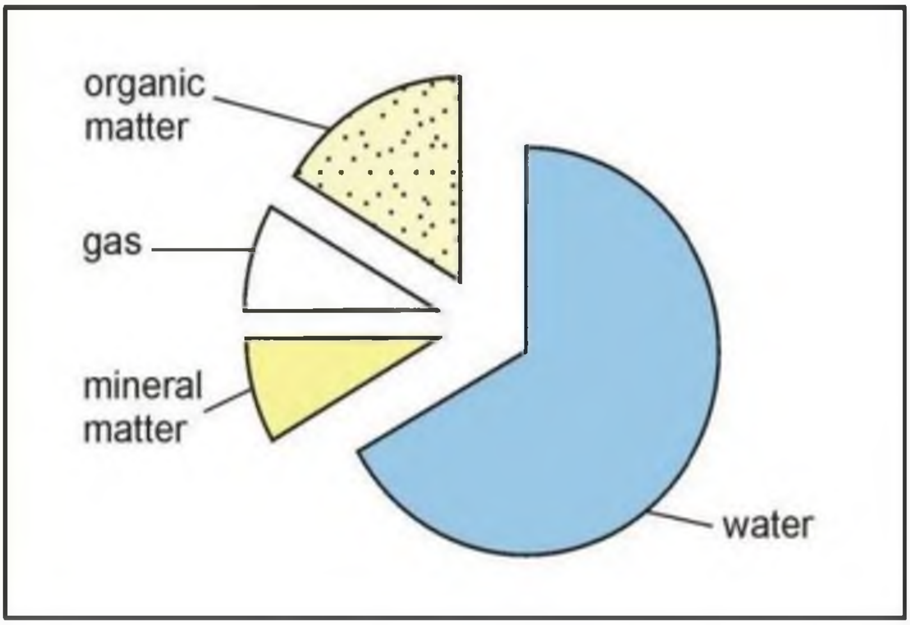

Figure 1.1 Composition of peat (Xuehui and Jinming, 2009)

The organic and mineral matters form the solid components of the peat. Organic component consists of the plant debris with high decomposition resistance such as plant roots, stems, leaves, spores, fruits etc. The mineral component of peat has two sources: transport agents such as running water and wind during accumulation processes, and chemical processes associated with the decomposition of plant materials.

Peatlands are geographically spread in almost all regions of the world (Figure 1.2). They are however more abundant in the higher latitude continents of Eurasia

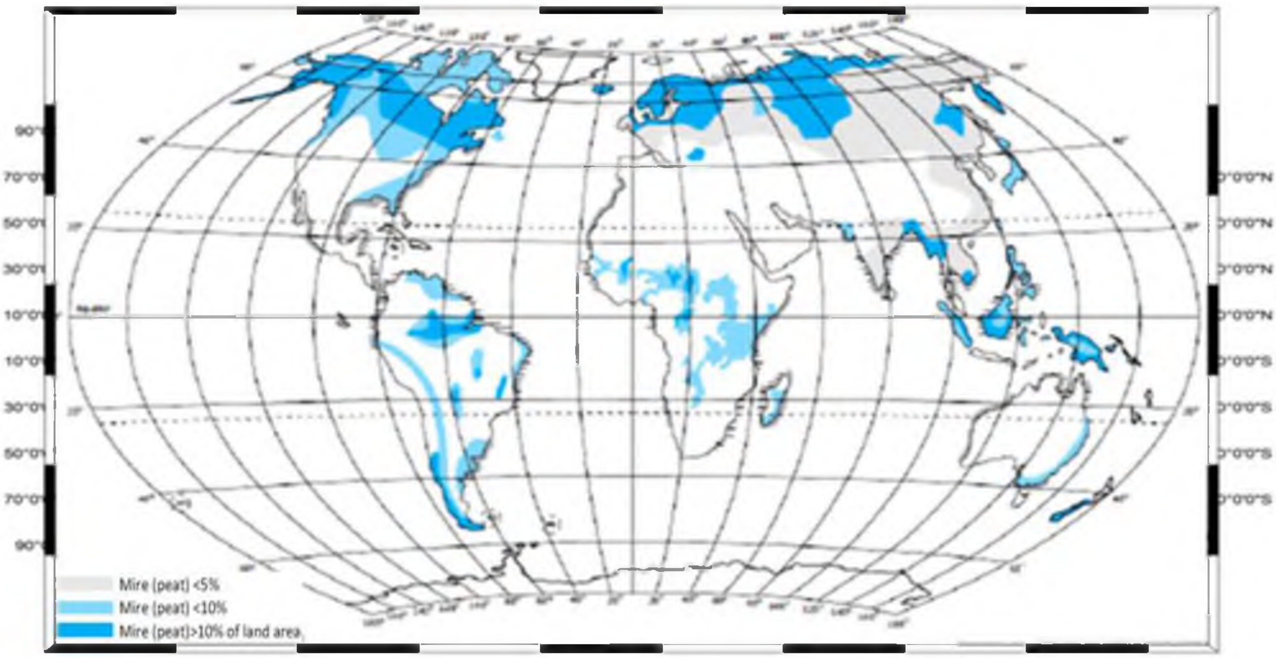

Figure 1.2 Global peat distribution (DOE, 2010)

and North America (Objective Corporate Research, 2005). It represents about 50% to 70% of the global wetlands (Finlayson and Spiers, 1999) making it the most widespread of all wetlands on the earth. With a deposit covering an area of about 1.4 million square km, Russia has the highest deposit of peatlands covering about 8% of the total land mass of the country (UNEP et al, 2005). In Southeast Asia, about 25 million hectares of the land are peat, representing about 60% of the global tropical peatland resources (UNEP et al, 2005) and nearly one-tenth of the entire extent of global peat resources (ASEAN, 2007). The largest Peatland deposit in Southeast Asia is found in Indonesia with over 70% of the total Peatland resources of the region (ASEAN, 2007).

Peatland is also available in many parts of Malaysia where it occurs in both highland and lowland region of the country. It is however more extensive in low lying poorly drained depression basins of the coastal areas. The total peatland area in Malaysia is approximately 2.4 million hectares, representing 8% of the country’s total land area (Mamit, 2009). About 1.6 million hectares of this are found in Sarawak, representing 13% of the state’s total land area. Peninsular Malaysia and Sabah have peatland areas of 0.7 million and 0.1 million hectares respectively. (Mamit, 2009). The largest deposit of peat soil in Peninsula Malaysia is found in the state of Johor as shown in Figures 1.3 and 1.4 (Van-Engelen and Huting, 2002).

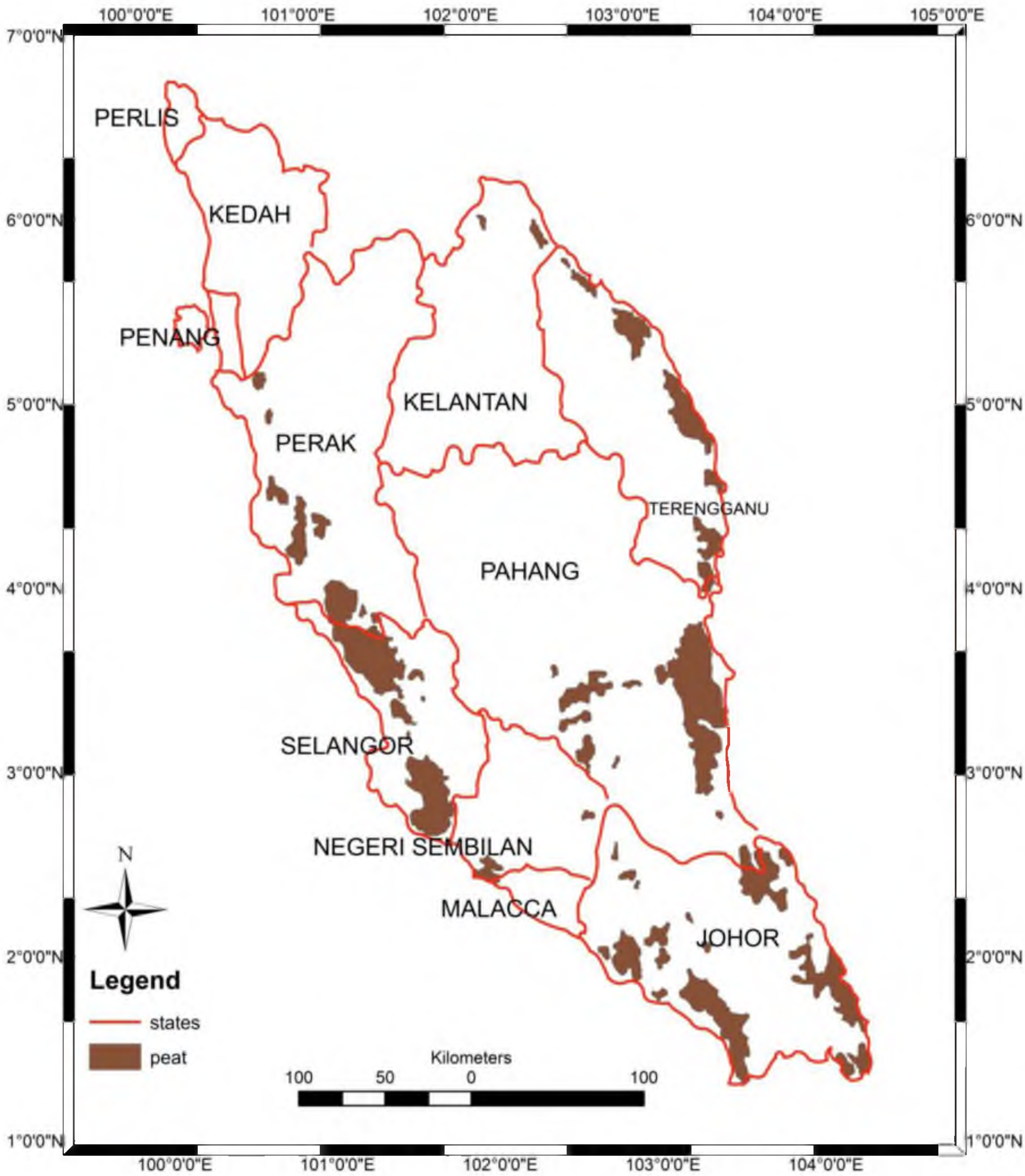

Figure 1.3 Distribution of peatland in Peninsula Malaysia (digitized from: UNEP et al., 2006)

Peat deposit is a very significant ecosystem that relates vegetation, climate and greenhouse gas. Being an accumulation of organic plant materials, the deposit serves as greenhouse gas regulation mechanism where carbon dioxide is absorbed and stored in the form of dead plant materials. Studies have shown that about 30% of

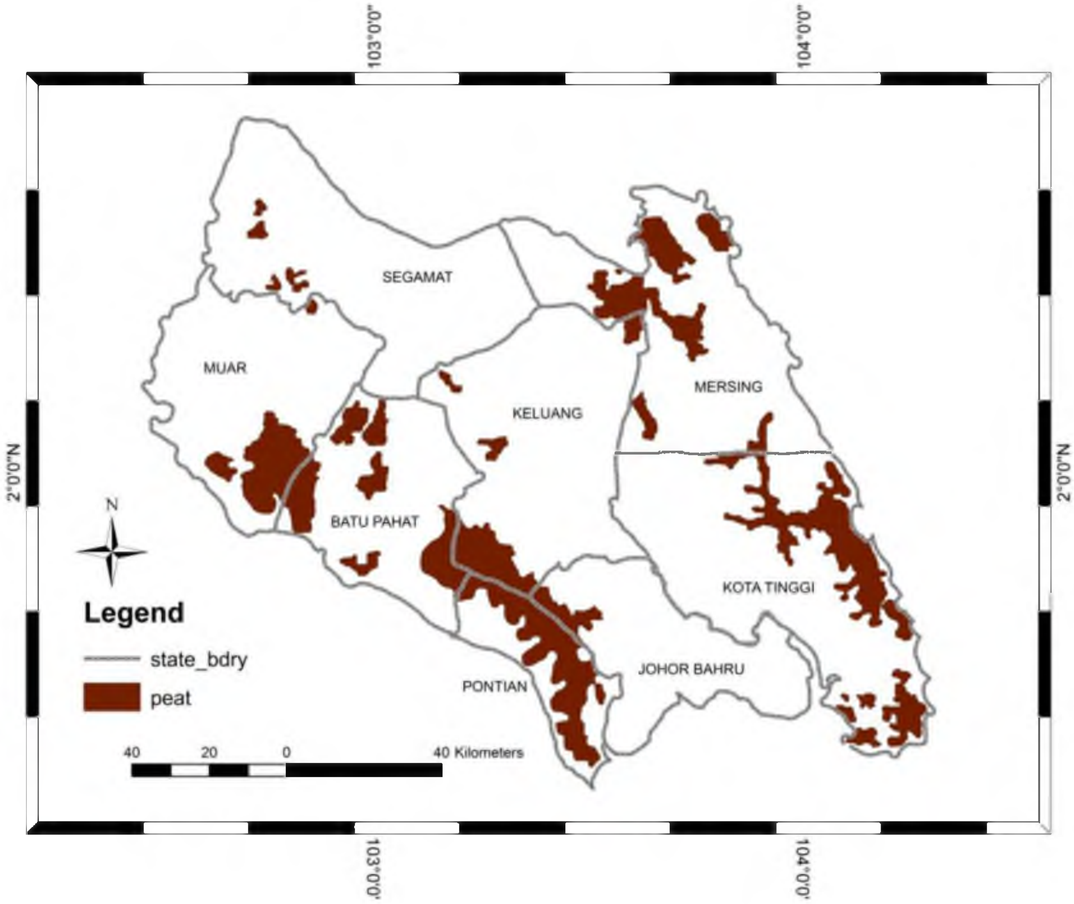

Figure 1.4 Distribution of peatland in the state of Johor. (digitized from: Wetland International, 2010)

terrestrial carbon is stored in the peat ecosystem (UNEP et al., 2005). About 15% of the global peatland carbon is stored in the tropical peatland alone (Mamit, 2009). Peatland drainage therefore leads to the oxidation and subsequent release of carbon dioxide into the atmosphere.

Peat soil has high water retention capacity (Mamit, 2009). The soil acts as a water stabilizing mechanism by releasing stored water during the dry season and rain water absorbed during heavy rainfall. This helps in releasing water stress and providing drainage for agricultural activities. Peat is highly flammable due to high carbon content. The soil can easily burn under low moisture condition. It therefore makes the soil to serve as energy resource that is useful in domestic heat production (Objective Corporate Research, 2005).

Thus peatland has a significant effect on millions of people around the world. Knowledge about the extent, quantity and composition of peat deposit is therefore of great importance in assessing the economic potentialities of the natural resources. Analysis of the stratigraphic sequences and petrophysical parameters of peatland is therefore needed for effective understanding of the distribution of its hydrological and chemical variables and the exchange of carbon within the ecosystem for sustainable development of the resource and its benefit to the present and future generations.

Being carbon storage ecosystem, invasive and destructive surveying of peatland will adversely have negative environmental effects as exposing the interior of the deposit will lead to the disturbance of the balance of atmospheric gas and contributes to the greenhouse gas emission (Page et al, 2011). Noninvasive geophysical techniques therefore offer tremendous advantages of environmental friendliness as they cause minimal disturbance thereby preserving the natural storage of the system. Ground Penetrating Radar (GPR) is the most extensively used noninvasive technique for mapping and estimating the composition and hydrological parameters of peatland. Thus there is the need for extensive research toward enhancement and effective development of this noninvasive surveying techniques with the aim of improving the various models applicable for the investigation of peatland parameters.

1.2 Trends in Ground Penetrating Radar (GPR) Surveying

The term Ground Penetrating Radar or ground probing radar refers to a range of electromagnetic techniques designed primarily for the location of objects or interfaces buried beneath the earth surfaces or located within a visually opaque structure (Daniels, 2004). GPR has become a useful and efficient instrument for gathering information about subsurface soil and geologic formations. It records continuous graphic profiles of the subsurface interfaces with a high degree of accuracy. The technique is particularly found to be successful in detecting subsurface geologic structures (Pauselli et al, 2010), buried archeological remains, subsurface fracture zones and cavities (El-Qady et al, 2005) etc.

The use of electromagnetic signal to determine the presence of a remote terrestrial metal object was first conducted by a German physicist, Christian Hulsmeyer in 1904 who used radio waves in a collision avoidance device for ships (Daniels, 2004). The first description of the use of radar in the location of buried object however appears six years later in Germany when Leimbach and Lowy patented the technique by burying a dipole antenna in an array of vertical borehole and comparing the magnitude of the signals received when successive signals are transmitted and received. A crude image was formed whose analysis led to the estimation of the depth of the buried interface. The technique was later used by Hulsenbeck for the first time in 1926 to determine the structure of buried features (Daniels, 2004). He noted that any change in dielectric properties of the subsurface, not necessarily involving conductivity, will also produce reflection and thus the technique, through realization of directional source, had advantages over the seismic method which has similar principle.

The subject generated considerable interest in the early 1970s when in the 1972 Apollo 17 mission whose primary purpose was to search for subsurface features of the moon, a coherent radar system was used to measure both the phase and the amplitude characteristics of the radar echo (Sensors and Software, 2012). The instrument was able to detect a layer-like dielectric discontinuity of about 1.3 to 1.0 at a depth as high as 1km. Since then to the present day, the method has effectively been used in space and other planetary exploration because of its ability to use remote non-contact transducers of the radiated energy rather than the ground contact type needed for seismic investigation.

There are two modes of operation of the GPR survey technique: shallow subsurface and deep borehole surveys (Annan, 2001). The shallow surface GPR, which is the most commonly used includes a hand pushed or pulled GPR chart (Figure 1.5), airborne and satellite surveying as well as high speed surveying from vehicle mounted radar. The deep borehole GPR survey involves the transmission of electromagnetic waves through a vertical borehole log. The reflected transient electromagnetic waves are received by the receiving antenna and the received signal can be analyzed to detect the subsurface discontinuity through the changes in the vertical electrical properties notably electrical conductivity and dielectric constant.

Figure 1.5 Multichannel GPR radar scanner (IDS DAD Inc, 2011).

GPR has a wide range of applications which expands steadily due to the development of more sophisticated computing devices. These include: outlining the foundation of building and other engineering structures, (Abbas, et al, 2009), mine detection (Bruschini et al, 1998), archeological investigation (Negri et al, 2008), location of water table, and characterization of subsurface contamination (Hamzah et al, 2009), road inspection (Loizos and Plati, 2007), stratigraphic studies of sedimentary formation (Bristow and Jol, 2003) and geomorphic controls of floodplain and surface subsidence (Poole et al, 2002).

The suitability of GPR as a subsurface survey tool for the imaging and characterizing the internal structure of peat deposit is strongly influenced by the petrophysical and electrical properties of the deposit. Peat is characterized by, high porosity and water content, and low magnitude of electrical conductivity due to the presence of highly concentrated inactive and strongly bound organic compounds. The low level of electrical conductivity enables larger depth of penetration within the peat deposit. Radar signal through the water saturated peat gives a high resolution image to a depth of about 16m is some cases (Lowry, et al, 2009). Thus GPR appears to be a highly suitable tool for peat analysis.

Remarkable achievements were recorded in peat land surveying with GPR. These include among others, peatland boundary delineation (Palletier et al, 1991), imaging dominant stratigraphic layers and carbon pool estimation (Dallaire et al, 2009) and evaluating spatial variability of free-phase biogenic gas of the peat soil (Strack and Mierau, 2010). All the previous studies however are conducted at the northern peatland, that is the largest peat deposit of the northern hemisphere that covers large areas of Canada, Finland, Sweden and Russia. The region is a low temperate zone where in most cases the deposit is covered by snow. Site-specific calibration of water content with dielectric constant is normally done on estimating the peat's water content while biogenic gas content is usually quantified using the complex refractive index model.

Peat soil in all the previous works was characterized based on Von post's scale of humification level owing to its suitability to the low temperate climatic condition. It is however observed that parametric properties of peat soil are greatly influenced by weather and climatic variables such as subsurface water condition, temperature and the type of peat-forming plant community (Xuehui and Jinming, 2009). There is therefore a need for extensive research toward development of a model for peatland surveying with GPR with respect to the tropical region of the earth for the purpose of maximizing the benefits of the potentialities of the tool particularly in Southeast Asia which accommodates the largest deposit of the soil in the tropical region.

1.3 Statement of problem

Petrophysical properties of peat soil such as water, biogenic gas and organic contents are vital parameters that define the physical and chemical properties of the soil. They determine the transformation processes taking place and its environmental impact on the deposit. They can be used to predict the effect of seasonal and climatic changes to the environment and the ecosystem in general. Mapping and modeling these properties are therefore strategic move toward effective acquisition of useful data necessary for sustainable management initiative of the resources.

Mapping petrophysical properties of peat is a major area of research with a wide range of application in geosciences, soil science, agriculture and remote sensing. It had been a labor intensive process that involved sampling for point observation with limited areas of coverage and broad sample spacing. The exercise was however simplified by the introduction of remote mapping devices such as optical and radar satellite imagery and surface radar scanners. The application of satellite images is however limited due to the fact that major physio-chemical transformations of the soil which influence the petrophysical properties occur at the subsurface deeply beyond the reach of the sensor's energies. Thus with regard to depth of coverage, fastness and continuous data acquisition over a larger area GPR is the most convenient technique of peat soil surveying (Doolittle and Butnor, 2009).

Unlike mineral soil, Peat has the most complex and unpredictable petrophysical properties that made it impossible to have a global prediction model. For instance even though there is a clear relationship between moisture content and apparent (measured) dielectric permittvity of peat as in the case of mineral soils, the former tends to deviate from the globally acceptable model relations that is found to be applicable to all mineral soils. Further research work on peat soil moisture content: dielectric permittivity relationship such as the work of Pumpanem and Ilvesniems (2005) and Persekian et al (2011) showed that both the nature and parametric coefficients of the model are site-specific due to the variation in climate and vegetation type of the peat-forming plant community.

Mapping relevant petrophysical properties of peat soil such as porosity and gas content are done based on the empirical relationship between the dielectric permittivity and moisture content. Despite the relevance of this relation however, literature evidences has shown that virtually no attempt is done to develop the model with respect to the tropical peat deposit of the Southeast Asian region. All the existing models are relative to high latitude peatland of the Northern Hemisphere. Considering the great variability in climate and vegetation type between the forest of the humid temperate region of the Northern Hemisphere and that of Southeast tropical region, it is believed that numerical modeling of these parameters with respect to Southeast Asian peatland will provide a bases for the surveying and mapping of the deposit noninvasively with GPR.

This work therefore involves the numerical modeling of dielectric permittivity of the peat soil and water content uniquely applicable to Southwestern Malaysian peatland which could however be applicable to any tropical peatland with same or similar vegetation cover. The model equation obtained was used to map the spatial distribution of water content within the area, a parameter of great economic and environmental relevance to the deposit.

One of the major environmental challenges facing Asian countries including Malaysia is the issue of forest fire facilitated by degradation of peatland. Forest fire occurred in many peatland forests at the pineapple plantation in Malaysia since 1970s (Nuruddin, 1998). The most prominent incidence is the 1997/1998 En-Nino disaster which affected many countries of the region. El-nino destroyed about 10% of the total peatland areas of Indonesia (UNEP *et al*, 2005). In that year alone, four incidences of forest fire were recorded in Peninsular Malaysia with a total burnt area of 425.27 hectares (Nuruddin, 1998). The Centre for International Forestry Research (CIFOR) in Jakarta, Indonesia, where the fire originated from, reported that the cause of the fire was from unconsolidated peat burning (Rowell and Moore, 2000).

A common forest fire preventive technique is the surveying of forest region to detect fire hotspot using remote sense imagery (Kudoh and Hosoi, 2003). Peatland forest fire is primarily caused by the accumulation of free-phase biogenic gas (Page et al, 2002), a product of microbial activities that is usually trapped within the pore space at the interior of the deposit. Thus subsurface mapping will by far be more effective.

Mapping biogenic gas is mostly done based on complex refractive index model (Strack and Mierau, 2010) which provides imperial equation relating the gas content with porosity, water content and the dielectric permittivites of the air and the soil. Although the model was found to be effective in gas content estimation, its dependent on large number of literature parameters results into high measurement uncertainty (Persekian et al, 2011). Experimental verification of the parameters on the other hand will make the overall experiment very cumbersome. In this work, a technique is developed for the mapping and identification of the subsurface free-phase gas accumulation based on the effect of the gas on radar signal velocity and attenuation rate.

Peat stratigraphy is a consequence of great variability in the decompositional resistance of various types and parts of peat-forming plants. The sequences of the stratigraphic layers are associated with the variation in nutrient content, acidity and humification levels of the deposit. The sequences were classified based on Von-Post scale of decomposition from least (H1) to highly decomposed (H10) (Huat et al, 2011) which is more detail of ASTM classification.

It is however observed that classification of peat on the bases of decomposition though suitable to high-latitude peat deposit, failed to adequately characterize tropical peat deposit owing to the variation in climate, vegetation and soil type (Wust et al, 2003). Thus a unique peat classification scheme more suitable to tropical peat deposit was adopted in classifying stratigraphic sequence detected from the radar image based on ash content

1.4 Objectives

The aim of this work is to develop a model for the mapping and analysis of petrophysical properties and delineate stratigraphy of tropical peatland with ground penetrating radar (GPR). The objectives of the study are:

(1) To develop an empirical model relationship between the moisture content and relative dielectric permittivity of Pontian peat soil.
(2) To map and estimate the spatial distribution of moisture content and delineate the spatial location of the water table of the peatland within the study area.
(3) To map the spatial distribution of biogenic gas content and estimate fractional volume of the gas within the interior of the deposit.
(4) To map and delineate the stratigraphic sequence of the peat deposit and classify the stratigraphic layers on the basis of ash and organic matter contents.

1.5 Significance of the study

One of the major advantages of GPR over other geophysical survey tools is its non-invasive and non-destructive nature. The tool is therefore cost effective in terms of finance, labor, and time. This study will provide a time and cost effective means of mapping the peat soil and identifying the areas that are susceptible to the hazard of forest fire. The study will serve as an assessment of the economic potentialities of the peat resources with respect to agriculture and possible production of commercial energy.

Stratigraphic analysis of GPR image will reveal regions of the peat deposit associated with high carbon content and give more accurate in situ stratigraphic depth information. The study will also contribute immensely to the development of agriculture by providing on-the-spot means of peat soil characterization with respect to soil fertility which is related to organic content, with high cost effectiveness and reasonable degree of accuracy. It will also play a significant role in monitoring and control of flood plains. The moisture content and stratigraphic analysis can reveal information about the soil subsidence drainage of the peat. This will serve as an indicator of the biophysical condition and the effect of varying climatic condition to the peat ecosystem.

The study will generally provide background information about the effective carbon storage, energy and economic potentialities of the peatland at all levels with respect to the study area, leading to effective management of the resources. The study will also contribute greatly to knowledge in related disciplines such as radiation science, geophysics, remote sensing and geomatic engineering and other areas that require accurate subsurface imaging and soil resources management.it will specifically expand the scope of application of GPR as a remote sensing and Geomatic Engineering tool.

1.6 Scope and limitations

This research was carried out in two phases: field and laboratory activities. the field operation involves scanning of four profiles with a multichannel IDS radar scanner. The profiles are 20m long each spaced at equal intervals of 4m. Two factors that determine the selection of the site and area of coverage are: accessibility and occurrence of water table sufficiently below the surface. The four profiles were chosen based on the need to achieve adequate coverage within the accessible regions of the area. The profiles were scanned with IDS scanner at a frequency of 200MHz.Core samples were collected from the surface to a depth of 3.5m at a depth interval of 0.1m. The collected samples were analyzed in order to determine the required geotechnical and physical properties of the soil with depth. All laboratory experiments were carried out based on American Standard for Testing and Measurement (ASTM) standard for peat soil.

The depth of penetration of the radar signal did not exceed 5m. This is due to the strong attenuation of the signal with the soil owing to its limitation by both the radar frequency and the soil characteristics of the study area. A careful frequency selection was made based on channel output selection to ensure maximum depth of coverage within a reasonable level of depth resolution. After several processing trials with the output radargrams from the three channels of the scanner (200MHz, 450MHz and 600MHz), observation showed that the 200MHz antenna gives a better resolution within the 5m depth, a mean peat thickness of deep peat in the study area according to Wetland International (2010). The channel was therefore selected and used throughout the work.

The reflexw interactive interpretation software was used for the interpretation and visualization of the data. The software is compatible with various data formats and is equipped with user-friendly processing interfaces.

1.7 Research contribution

The academic and industrial contributions of this research work are summarized as follows:

- A model for application of GPR in the assessment and quantitative estimation of water content of Pontian peat soil is developed based on the derived empirical equation. The equation is applicable to any peat deposit of the same climate condition having the same vegetation type cover.
- The developed model also provides the bases for the application of GPR in the estimation biogenic gas content of tropical peat soil. Thus the gas content of the peat deposit can be estimated from a remote surface measurement. Biogenic gas mapping can be used to identify regions of the deposit that are prone forest fire due to high accumulation of the inflammable gas. The gas mapping can also be used to assess the level of impact of the deposit to greenhouse gas emission.
- The work revealed for the first time, the thickness and the level of humification of Pontian peat soil from surface radar measurement. This is in contrast to the invasive and destructive core analysis technique which is labor intensive and less accurate. The humification level of peat soil is related organic content which determine nutrient content of the soil, a parameter of great importance to agricultural and horticultural application of the soil.
- The work also provides for the first time, information about the stratigraphic sequence of Pontian peat deposit on the bases of ash content, another important parameter that determine the agricultural yield of the soil.

1.8 Thesis organization

This thesis is divided into eight chapters. Chapter one introduces the research work by presenting the background of the study, problem statement, research objectives, significance of the study, scopes of the study and thesis organization. Chapter two covers literature review. This includes review of literatures related to the application of GPR in peat mapping with particular emphasis on water content, biogenic gas and stratigraphic mappings. Chapter three describes the research methodology and includes a brief description of the study area, research design, GPR system description, laboratory experimental procedure, field procedure, method for data collection, data processing strategy, interpretation procedure and method for data analysis. Chapter four to seven covers respectively the four objectives of the research these involve step by step report of the data processing and analysis relative to the objective including laboratory procedures used in order to achieve the objective. Chapter eight covers in general the conclusion and recommendation.

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