ISSN 2500-0632 (ON-LINE)
MINING SCIENCE AND TECHNOLOGY (RUSSIA)
GORNYE NAUKI I TEKHNOLOGII
2020;5(3):224-234

MISIS National University of Science and Technology

ОРИГИНАЛЬНЫЕ СТАТЬИ / ORIGINAL PAPERS

DOI: 10.17073/2500-0632-2020-3-224-234

Assessment of applying VLF geophysical method to determine the peat deposit thickness

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Abstract: Peat deposits accumulate large reserves of carbon and play an important role in formation of global climate, biosphere, and hydrological conditions. High degree of knowledge of peat reserves is one of the prerequisites for scientifically based and economically viable wetland management. For economically efficient commercial activity, an enterprise developing a peat deposit must be confident in the availability of sufficient and high-quality commercial peat reserves. Therefore, the topic of studying the thickness of peat deposits is quite relevant. The paper analyzes the experience of using the geophysical method called VLF ("very low frequency") to study the thickness of peat deposits. The method consisted of using a VLF receiver to measure the properties of VLF emitted by the peat deposit and the underlying mineral ground. The study was carried out at the Beloe Lake peat deposit in the Tukayevsky district of Tatarstan, at three peat areas of different depths: deep-lying (over 3 m), intermediate (1.5 – 3 m), and shallow (up to 1.5 m). The depth was confirmed by direct measurements in the wells. Low-frequency (VLF) measurements were carried out along the geophysical paths at each area of the peat deposit. The data were processed using the NAMEMD (Noise Empirical Decomposition) method and converted to resistivity and depth values using the specialized software. The study showed that the resistivity differs significantly between the areas of deep-lying and shallow peat. The resistivity varies depending on the peat thickness and the thickness of the buried wood horizons. In the horizons of deep-lying peat, the resistivity is strongly influenced by the degree of peat decomposition, its natural density and moisture. The presence of peaks and their height on the data interpretation plots characterizes the number and thickness of the horizons of buried wood in the peat deposit. With increasing depth of peat occurrence, the resistivity increases significantly. However, in the shallow areas, it does not show differences, being characteristic for the deep-lying peat area. This proves that the VLF method works correctly in peat layers and is capable to indicate the peat thickness, the number and thickness of the buried wood horizons.

Keywords: peat thickness, peat horizons, geophysical method, conductivity, VLF method, resistivity, ANOVA method, Tukey's HSD test

For citation: Yakonovskaya T. B., Zhigulskaya A. I., Yakonovsky P. A. Assessment of applying VLF geophysical method to determine the peat deposit thickness. *Gornye nauki i tekhnologii = Mining Science and Technology (Russia)*. 2020;5(3):224-234. (In Russ.) DOI: 10.17073/2500-0632-2020-3-224-234

Оценка использования геофизического метода VLF для определения мощности торфяного месторождения

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Аннотация: Торфяные месторождения аккумулируют большие запасы углерода и играют важную роль в формировании глобального климата, биосферы и гидрологии. Высокая степень изученности торфяных запасов является одной из предпосылок научно обоснованного и экономически целесообразного управления водно-болотными угодьями. Для экономически эффективной хозяйственной деятельности предприятие, разрабатывающее торфяную залежь должно быть уверено в наличии достаточного и качественного объема промышленных запасов торфа. Поэтому тематика исследования мощности торфяных месторождений является достаточно актуальной. В статье анализируется опыт использования геофизического метода, называемого VLF («очень низкая частота»), для исследования мощности торфяных месторождений. Метод заключался в использовании приемника VLF для измерения свойств VLF, излучаемых торфяным месторождением и подстилающим минеральным грунтом. Исследование было проведено на месторождении торфа «Озеро Белое» Тукаевского района Татарстана на трех разных по глубине участках торфа: глубокозалежного (свыше 3 м), среднезалежого (1,5–3 м) и мелкозалежного (до 1,5 м). Глубина была подтверждена прямым измерением по скважинам. Низкочастотное измерение VLF проводилось вдоль геофизических трасс на каждом участке торфяной залежи. Данные были обработаны с использованием метода NAMEMD (эмпирическая декомпозиция шумовых сигналов) и преобразованы в значение и глубину удельного сопротивления с использованием специализированного программного обеспечения. Исследование показало, что удельное сопротивление значительно отличается по участкам глубокозалежного и мелкозалежного торфа. Удельное сопротивление изменяется в зависимости от толщины торфа и мощности горизонтов погребенной древесины. В горизонтах глубокозалежного торфа на величину удельного сопротивления оказывают сильное влияние степень разложения торфа, его естественная плотность и влажность. Наличие пиков и их высота на графиках интерпретации данных характеризуют количество и толщину горизонтов погребенной древесины в торфяном месторождении. С ростом глубины торфа сопротивление значительно растет. Однако на мелкозалежных участках оно не проявляет различий, как в области глубокозалежного торфа. Это доказывает, что метод VLF правильно работает в слоях торфа и способен указывать толщину торфа, количество и мощность горизонтов погребенной древесины.

Ключевые слова: мощность торфа, горизонты торфозалежи, геофизический способ, проводимость, метод VLF, удельное сопротивление, метод ANOVA, тест HSD Тьюки

Для цитирования: Яконовская Т. Б., Жигульская А. И., Яконовский П. А. Оценка использования геофизического метода VLF для определения мощности торфяного месторождения. *Горные науки и технологии*. 2020;5(3):224-234. DOI: 10.17073/2500-0632-2020-3-224-234

Introduction

Peat bogs are common elements of the mineral resources base of the regions of Russia. However, different constituent entities of the Russian Federation differ in the degree of exploration maturity of the peat resources. Peat deposits accumulate large reserves of carbon and play an important role in formation of global climate, biosphere, and hydrological conditions. High degree of knowledge of peat reserves is one of the prerequisites for scientifically based and economically viable wetland management. For economically efficient commercial activity, an enterprise developing a peat deposit must be confident in the availability of sufficient and high-quality commercial peat reserves [1].

Notice that intensive geological exploration of peat deposits was carried out only in the Soviet period of Russia's development, whereas at present time such studies are not carried out due to their high cost and labor intensity. When preparing detailed design for the development of a peat deposit, design organizations use an outdated information base of peat funds of 1952, 1989, and 2000. A great fault of the information contained in the peat funds is the lack of data on the thickness of a particular deposit (peat depth), its stumpiness (the number and thickness of buried wood horizons), and the type of underlying mineral ground. For this reason, the amount of knowledge about the number, scale, and thickness of peatlands in the Russian regions and their spatial variability varies greatly by region. It is also likely due to different standards, instruments, and measurement methods.

Exploration maturity of peat resources in Tatarstan is 78 %. The figures on the total area and the number of peatlands in Tatarstan differ. For example, in the peat fund of 1952, the area of the supposed fund of peat reserves was 20 thousand hectares, and the number of deposits was 608. The 1989 peat fund data indicate the area of 20.6 thousand hectares, whereas according to the 2000 peat fund, the area is already 30 thousand hectares, comprising 900 deposits [1, 2]. However, the thickness and other characteristics of peat deposits vary widely, and are not fully reported for some deposits. In addition, many peat deposits in Tatarstan border on hydrocarbon deposits.

In this research, the authors, when studying a peat deposit, propose to use a geophysical method, which allows determining the thickness of a peat deposit with high accuracy. The geophysical method is based on the use of very low frequency electromagnetic wave, therefore it is also called the VLF-EM method or simply the VLF method. The VLF-EM method was originally developed for underwater navigation. However, it is also used for geophysical exploration due to its ability to penetrate the earth's surface and spread over very long distances.

VLF-EM propagation within the earth can actuate any underground conductor to generate secondary electromagnetic field that can be detected by a VLF receiver. The VLF method actually uses equipment that has the ability to receive and measure the difference between primary and secondary electromagnetic radiation in terms of phase or polarization. The measured electromagnetic energy emitted by an underground conductor depends on its conductivity and resistivity. Peat, an underlying mineral ground, and a buried wood layer have different conductivity and, therefore, will have different polarization [3].

The purpose of this study was to assess the possibility of using the VLF method to study the variability of the peat occurrence depth and determine stumpiness of a peat deposit.

Research methodology

The research was carried out at the "Lake Beloe" peatland located in the Tukayevsky district of Tatarstan. This is one of the largest deposits in terms of reserves, the individual areas of which differ in depth of peat occurrence, that is, *A* area – deep-lying peat (over 3 m), *B* – intermediate (relatively deep) peat (1.5 – 3 m), and *C* – shallow peat (0 – 1.5 m) (Fig. 1). The "Lake Beloe" is a typical, for the conditions of Tatarstan, high-ash deposit of lowland herbal group of lake-type formation. This is the only peat deposit developed since 2009 for agricultural purposes.

The tools used in the research include: peat auger, peat deposit map, GPS, VLF-EM receiver, and computer with Inv2DVLF software installed [4 – 6]. The main data collected were: peat depth and VLF data. The VLF data consisted of in-phase and quadrature signal components [7]. The in-phase component of the signal is the magnitude of the polarized angle of the secondary winding field to the vertical primary field. In turn, the quadrature component of the signal is the relation of the elliptical axes to the plane of polarization [6, 8]. The VLF measurements were consistent with the general VLF geophysical survey method. The measurement was carried out in 16 lines in three directions of the research. At thow Areas of the peat deposit (*A*, *B*), 5 lines were available, whereas in Area *C*, 6 lines. The length of the geophysical survey line ranged 200 to 500 m, while the intervals between the lines ranged 10 to 20 m. The peat depth was measured by direct method, in boreholes, which were located every 80 meters in all the geophysical survey lines. In some locations where the variability of peat depth increased dramatically, the spacing between the boreholes was reduced (Fig. 1). The collected VLF data were analyzed using the NAMEMD method to eliminate the effect of noise in the observations [9, 10]. The denoised data was then inverted using Inv2DVLF [6, 11] to obtain an estimate of 2D resistivity along the lines of each peat Area.

Discussion of findings

Inv2DVLF software estimates in-phase and quadrature values and predicts vertical sequential

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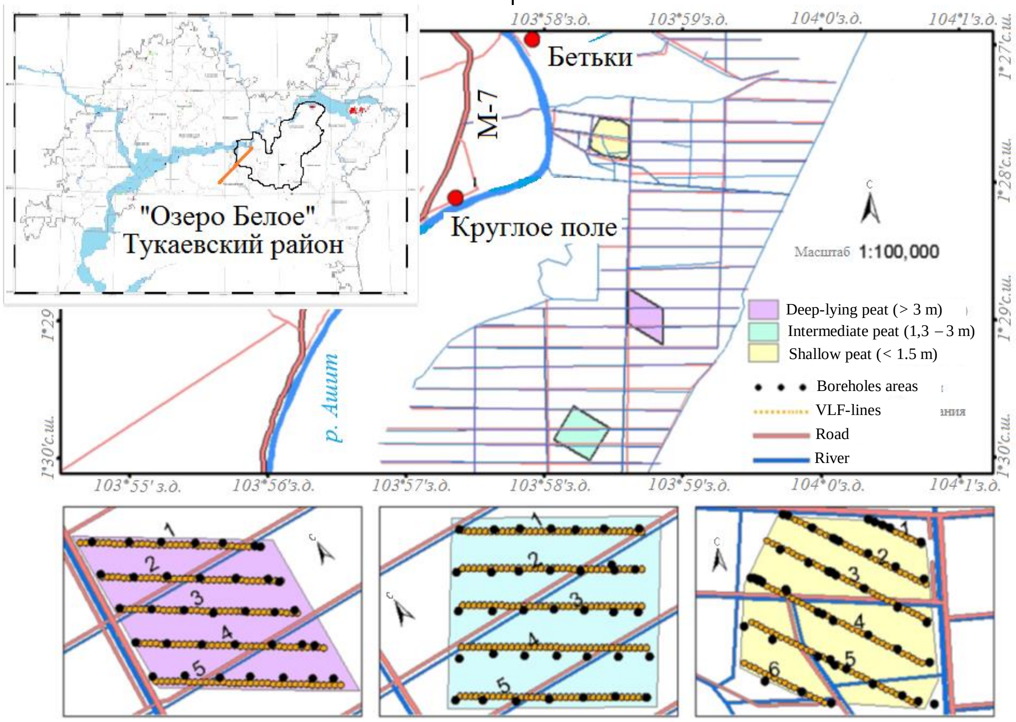
resistivity values along each geophysical survey lines. The predicted resistivity dataset consists of 8 vertical z-positions to depth: 0.5 m, 1.1 m, 1.52 m, 2.2 m, 2.58 m, 3.15 m, 3.6 m, and 4.72 m. These depths can vary slightly depending on the frequencies used in the VLF method and the initial resistivity values. During the study, the initial resistivity, according to the VLF method, was 15 ohmmeters. Fig. 2 shows the position of the predicted resistivity by Inv2DVLF.



Deep-lying peat (*A*) Intermediate peat (*B*) Shallow peat (*C*)

Fig. 1. Map of the study territory and sampling Areas (*A*, *B*, *C*)

The predicted resistivity values for each geophysical survey line were interpolated vertically using geostatistical software to generate 2D vertical planes. The result of interpolation, in the form of resistivity, is shown in Fig. 3, and the peat thickness is shown as a line on each graph. The peaks on the line (green) show the number and thickness of the buried wood horizons. Peat deposits in their natural state are porous, moisture-saturated, varying in density with different inclusions (stumps, stones, lenses of water, sand, clay, etc.) sedimentary rock, within which very large variability of electrical conductivity is observed [3]. Correspondingly, electrical conductivity of peat, various inclusions, and underlying ground differs [11–14]. For example, dry wood as high electrical resistance and is a dielectric, whereas being in a peat deposit, wood is saturated with water and loses its dielectric properties. In addition, the resistance of different species of wood is also different; for example, the resistance of pine at moisture of 20% is $3 \cdot 10^8$ Ohm/cm, that of birch, $4.2 \cdot 10^{10}$ Ohm/cm; at moisture of 100 %, the resistance of pine is $1.8 \cdot 10^5$ Ohm/cm, and that of birch, $2 \cdot 10^7$ Ohm/cm. The higher the moisture content of the deposit (80 – 90 %), the lower the resistance and the higher the electrical conductivity [11]. Thus, the specific electrical conductivity of peat has strong correlation with its properties (moisture content, degree of decomposition, stumpiness, botanical and agrochemical composition, ash content, etc.). In view of the above, a reasonable question arises: "How to distinguish the electrical conductivity of peat, buried wood, and the underlying mineral ground?" [15–17]. When studying the peat deposit by the VLF method, when interpreting the obtained resistances on the graphs presented in Fig. 3, peaks appear, the height of which enables determining the thickness of the buried wood horizons.

Visually, it is difficult to recognize the correlation between peat thickness and resistivity by the VLF method (Fig. 3).

Basically, most graphs indicate that resistivity decreases with increasing depth of the peat deposit occurrence. However, this does not correlate with the peat thickness. At the same time, none of the graphs shows direct correlation between the thickness of peat layers and the resistivity.

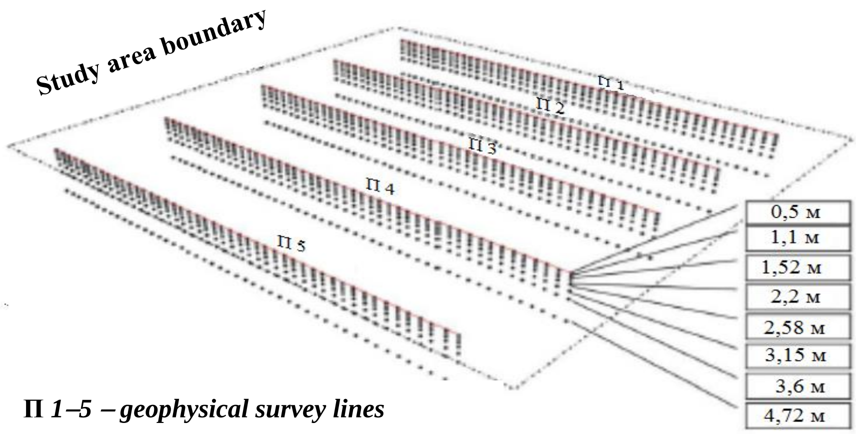


Fig. 2. Positions of measured resistivity values along cross-sections generated by Inv2DVLF software (each VLF measurement point generates 8 points of the peat mass computational resistivity (these depths differ insignificantly depending on the VLF frequency and the initial resistivity determined before the processing)

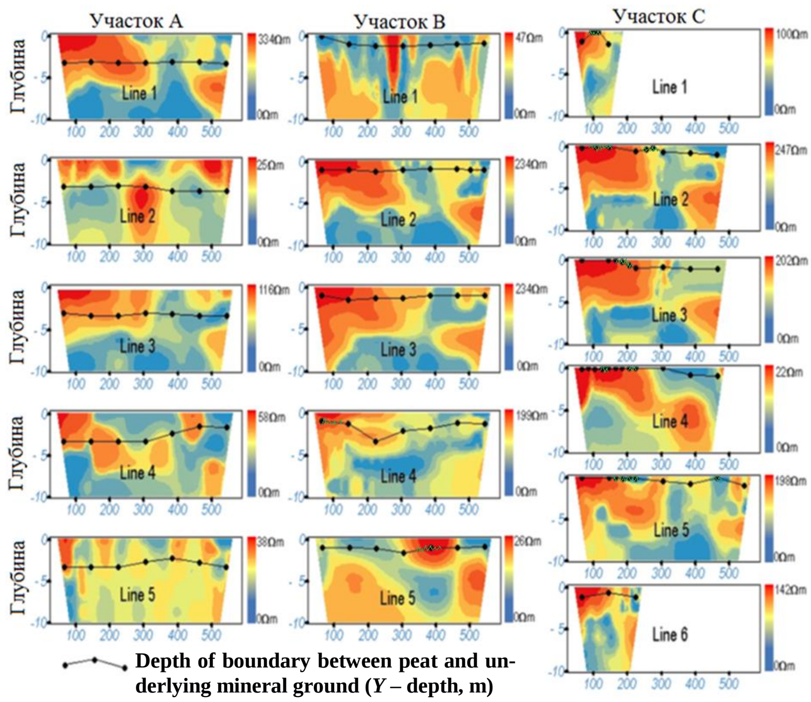


Fig. 3. Vertical planes of resistivity in Areas of the peat deposits

The changes in resistivity are very different across all three Areas of the peat deposit. In the Area A, high resistivity (red) is more concentrated in the upper layers, while in other layers it is lower. In addition, most graphs show high resistivity at the beginning of the lines. On lines *1* through 5 of the Area C, peaks in the realms of high resistance jumps are highlighted in green that indicates the presence of "islands" of buried wood of average thickness of 0.5 m. On lines 4 and 5 of the Area B, there are also peaks in resistivity, which indicate that the layer of buried wood is insignificant (compared to the Area *C*). It should be noted here that 19 % of the territory of Tatarstan is covered with forest, and on peat deposits, areas of woody vegetation are found as "islands". In view of this, peat deposits of Tatarstan have low stumpiness. High stumpiness is found in shallow deposits or "islands" in the surface horizons of a peat deposit, such as, for example, in the investigated "Lake Beloe" deposit. Peat at the Lake Beloe deposit is of lacustrine origin, and its greatest depth of 5m was determined by direct method (in the well in the center of the deposit). The Area A with the depth of 4.72 m is located within the relict lake outline; therefore there are no horizons of buried wood there. An explanation of the data on the resistivity and thickness of peat, as well as the statistical description and assessment are presented in Table 1. For the statistical analysis, the ANOVA method and Tukey's HSD test [18-20] (the test of true significance) were used, which tracks the frequency of false positive results with correcting for the effect of multiple comparisons. This means that if a check is performed at the 0.05 level, then for all pairwise comparisons, the probability of getting one or more false-positive results is 0.05.

On the whole, the average resistivity tends to decrease as the peat layer thickness increases. This is demonstrated by the data in Table 1. The linear graph in Fig. 4*a* shows a tendency for resistivity to decrease with depth representing three Areas and the average of the total. The full lines show similar declining trend, which can be interpreted using the equation:

Area *A*:

$$y = -4{,}849 \ln x + 35{,}709,\ R^2 = 0{,}8421; \quad (1)$$

Area *B*:

$$y = -6{,}305 \ln x + 40{,}915,\ R^2 = 0{,}9453; \quad (2)$$

Area *C*:

$$y = -7{,}255 \ln x + 43{,}428,\ R^2 = 0{,}9318; \quad (3)$$

Average value:

$$y = -6{,}136 lnx + 40{,}017,\ R^2 = 0{,}919, \quad (4)$$

where y is the resistivity; x is the peat horizon thickness, m.

Table 1

Predicted resistivity for the studied Areas of the "Lake Beloe" peat deposit

Depth	Area *A*		Area *B*		Area *C*	
	Significance	RMSD (Std Dev)	Significance	RMSD (Std Dev)	Significance	RMSD (Std Dev)
0.5	33.72	50.92	39.94	49.56	41.98	48.98
1.1	33.97	44.41	37.49	43.56	40.26	41.88
1.52	30.75	33.95	32.82	33.44	35.28	32.57
2.2	26.01	22.11	28.60	23.10	28.01	22.24
2.58	25.06	23.96	25.48	21.24	24.97	18.22
3.15	21.57	18.42	22.93	22.75	21.92	16.27
3.6	14.81	9.85	16.90	11.16	16.61	9.09
4.72	18.58	6.57	17.58	6.81	16.89	5.43

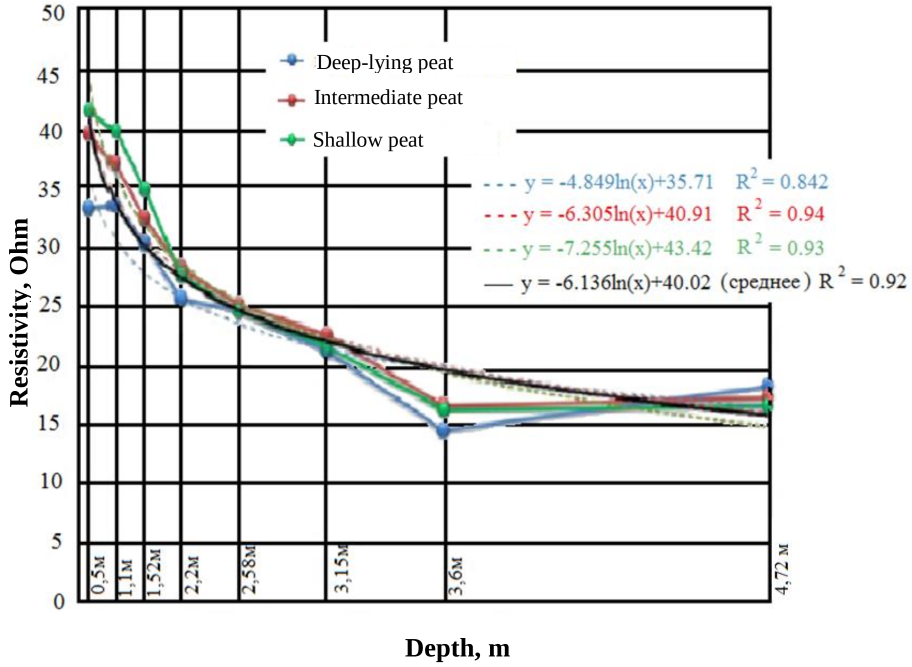


Fig. 4. Peat depth and peat resistivity

The graph shows that the deeper from the surface the peat occurs, the lower its resistivity. This means that the resistivity of the deep-lying peat horizon is lower than that of the shallow peat horizon. This is explained by the material density, because the deep-lying peat horizon mainly consists of dense peat with high degree of peat decomposition and the underlying ground. The higher the peat density, the easier the electric current passes through it. Thus, the higher conductivity, the lower resistivity. The variability of the peat thickness in the three Areas of the peat deposit (A, B, C) is shown in Fig. 4b.

By comparing the average resistivity value between the depths of peat occurrence (Table 2) and using the ANOVA statistical method, the statistically significant difference in the resistivity was obtained.

Table 2

Data of the comparison of the average resistivity values for the peat Areas based on the ANOVA method

Comparison	**Sum of squares**	***df***	**RMSD**	***F***
Outside (between) the peat Areas	8387.9	2	4193.9	4.53
Within the peat Areas	5854862.5	6.323	926.8	
Total	5863250.4	6.324		

Table 3

Data of the comparison of the average resistivity values for the peat Areas based on the Tukey HSD test

Comparison between the peat areas		**Average difference**	**Std. error**	**95% probability**	
				lower bound	**upper bound**
A	B	−2.16	0.97	−4.44	0.12
	C	−2.68*	0.93	−4.85	−0.51
B	A	2.16	0.97	−0.12	4.44
	C	−0.52	0.93	−2.7	1.65
C	A	2.68*	0.93	0.51	4.85
	B	0.52	0.93	−1.65	2.7

Note: Each value with an asterisk indicates significant difference in the peat depth variation and the trend of difference in resistivity with depth

Table 4

Data of the comparison of the average resistivity values for each peat Area based on the ANOVA method

Peat Area	Comparison	Sum of squares	df	RMSD	F
A	Between peat depths	84481.2	7	12068.7	13.3
	Within peat depths	1771570.5	1.952	907.6	
	Total	1856051.7	1.959		
B	Between peat depths	127238.2	7	18176.9	20.3
	Within peat depths	1743355.2	1.952	893.1	
	Total	1870593.4	1.959		
C	Between peat depths	160056.2	7	22865.2	23.7
	Within peat depths	1880673.3	1.952	963.5	
	Total	2040729.5	1.959		

Table 5

Average resistivity by depth and Tukey HSD test result for each peat area

Depth, m	Area A	Area B	Area C
0.5	33.7	39.9	41.9
1.1	33.9	37.5	40.3
1.52	30.7	32.8	35.3
2.2	26.0	28.6	28.0
2.58	25.1	25.5	24.9
3.15	21.6	22.9	21.9
3.6	14.8	16.9	16.6
4.72	18.6	1.6	16.8

The HSD test (Table 3) was carried out between Area A (deep-lying peat) and Area C (shallow peat). However, there is no difference between Area A (deep-lying peat) and Area B (intermediate peat), and between Area C (shallow peat) and Area B (intermediate peat). Comparison of the three lines shows that the line representing the deep-lying peat Area (blue line) is the lowest among the others, followed by the lines of the intermediate peat Area and the line of the shallow peat Area, respectively. This difference is due to close relationship with peat watering and acidity. The peat thickness correlates with its moisture and acidity. Peat Area A is more watered than peat Area C. In addition, peat in Area A is more acidic, and the higher water content of peat, the lower its resistivity.

The most important result is the data of comparison between peat depths [21]. When the resistivity is compared between different peat depths (Table 4), statistical significance of the resistivity difference between these depths also takes place. The difference in resistivity between the different peat depths ($p < 0.05$) for all Areas was determined based on the Tukey's test results, presented in Table 5. The test results shows in detail changing the resistivity with depth. That is, the resistivity of the upper peat layer begins to decrease and then demonstrates significant change with depth (indicating the boundary between the peat and the underlying mineral ground). The Table shows that in Area A, the resistivity at depths of 0.5 m, 1.1 m, 1.52 m does not differ statistically, but significantly changes starting from depths below 4 m. In Area B, the resistivity is statistically the same at depths of 0.5 m, 1.52 m and 2.58 m, and starts to significantly change when the depth is below 3 m. The difference, as shown in the statistical test result, is closely related to the characteristics of the peat Areas.

Area A (deep-lying peat) has peat thickness of 3 to 4.72 m, and the latter figure indicates the boundary between the peat and the underlying mineral ground. In turn, the depth of peat in Area B (intermediate peat) ranges 1.5 - 3 m, so the average resistivity tends to decrease and demonstrates significant change at the level of 2.8 m. In Area C (shallow peat), the resistivity also markedly decreases at the depth of the peat boundary with the underlying mineral ground.

These facts indicate that the resistivity measured by the VLF method is capable to indicate depth intervals corresponding to peat layers. The resistivity in the upper layer (close to the surface) differs markedly from that at greater depths, in layers lying farther from the surface. The abundance of organic matter contained in peat and the presence of water make peat porous and lighter in density than mineral ground. Consequently, peat tends to demonstrate higher resistivity compared with the ground.

Conclusion

The VLF method is applicable in geophysical study of peat deposits and shows variability of peat resistance by depth. However, from the authors' point of view, it would be more informative to use the GPR (Ground Penetrating Radar) method as a supplement to VLF [22, 23]. The resistivity measured based on the VLF method tends to decrease as the depth of the peat deposit increases. The average resistivity of deeper horizons of the peat deposit is significantly lower than that of shallow horizons of the deposit. With depth (vertically) resistivity of peat in the Areas of deep-lying peat (below 3 m) and intermediate peat (1.5 – 3 m) remains statistically unchanged until the depth at which the peat turns into the underlying mineral ground (bottom).

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