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STUDY OF INFLUENCE OF THE MAIN GROUND PROPERTIES ON GROUNDING DEVICE RESISTIVITY

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ИССЛЕДОВАНИЕ ВЛИЯНИЯ ОСНОВНЫХ СВОЙСТВ ГРУНТА НА СОПРОТИВЛЕНИЕ ЗАЗЕМЛЯЮЩИХ УСТРОЙСТВ

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specific electrical resistance of ground, equivalent resistivity of ground, vertical grounding device, multilayer ground, seasonal climate coefficient, design of grounding devices, resistivity of grounding devices, ground porosity, geology.

The value of resistivity of a grounding device depends on specific electrical resistance of ground, therefore, when designing grounding devices it is necessary to take into account layered structure of ground. The paper presents results of a study of influence of the main ground properties such as ground structure and composition, temperature and humidity, that depend on climatic and weather conditions of terrain and season, ground porosity, presence of salts, alkaline and acid residues, depth of occurrence of groundwater by the value of their specific electrical resistances. On example of ground structure of northern and southern areas of Perm region, effectiveness of a method for calculating grounders over the upper and lower layers of ground is shown. The results of calculations in a form of graphical functions of resistance of a vertical grounding device versus its length in a multilayered ground are given. For northern areas of Perm region the use of simplified techniques in calculation of grounding devices only over the upper layer of ground leads to significant deviations in calculated values from the actual ones. The effect of climatic conditions on specific electrical resistance of ground is analyzed. The results of study of influence of rock porosity on specific electrical resistance of ground are presented in example of such rocks as sand, sandstone and limestone. It is shown that specific electrical resistance varies depending on different values of ground porosity in wide ranges: at high values of ground porosity its specific electrical resistance decreases sharply due to the fact that pores can be filled with liquid while increasing conductivity of ground. Thus, this paper substantiates a thesis about the need to take into account basic properties of ground such as stratification, seasonal climate coefficient and porosity, when designing grounding devices of electrical units to ensure safe electrical conditions. In addition, it is shown that considering heterogeneity of the earth greatly improves accuracy of calculation of grounding devices and reduces cost of their design.

Ключевые слова:
удельное электрическое сопротивление грунта, эквивалентное сопротивление грунта, вертикальный заземлитель, многослойный грунт, климатический коэффициент сезонности, проектирование заземляющих устройств, сопротивление заземляющего устройства, пористость грунта, геология.

Величина сопротивления заземляющего устройства зависит от удельного электрического сопротивления грунта, поэтому при проектировании заземляющих устройств необходимо учитывать слоистое строение грунта. В статье представлены результаты исследования влияния основных свойств грунтов: его структуры и состава; температуры и влажности, зависящих от климатических и погодных условий местности, времени года; пористости грунта; присутствия солей, щелочных и кислотных остатков; глубины залегания грунтовых вод – на величину их удельных электрических сопротивлений. На примере структуры грунтов северного и южного регионов Пермского края показана эффективность метода расчета заземлителей по верхнему и нижнему слоям грунта. Приведены результаты расчета в виде графических зависимостей сопротивления вертикального заземлителя от его длины в многослойном грунте. Для северных районов Пермского края использование упрощенных методик при расчете заземляющих устройств только по верхнему слою грунта приводит к существенным отклонениям расчетных значений от фактических. Выполнен анализ влияния климатических условий на удельное электрическое сопротивление грунта. Представлены результаты исследования влияния пористости горной породы на удельное электрическое сопротивление грунта на примере таких горных пород, как песок, песчаник и известняк. Показано, что удельное электрическое сопротивление в зависимости от разных значений пористости грунтов меняется в широких диапазонах: при больших значениях пористости грунта его удельное электрическое сопротивление резко снижается, так как поры могут заполняться жидкостью, при этом увеличивая проводимость грунта. Таким образом, в данной статье обоснован тезис о необходимости учета основных свойств грунта: слоистости, климатического коэффициента сезонности и пористости – при проектировании заземляющих устройств электроустановок для обеспечения условий электробезопасности. Кроме того, показано, что учет неоднородности земли значительно повышает точность расчета заземлителей и удешевляет их проектирование.

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Introduction

Resistance of a grounding device depends on specific resistance of ground. It determines properties of soil in terms of its electrical conductivity. The smaller it is, the less resistance of spreading and, therefore, the more favorable conditions for grounding device. Depending on composition (clay, limestone, sand), size and density of adjacent particles, humidity and temperature, presence of soluble chemicals (acids, alkalis, rotting products etc.), the resistivity of soils varies in wide range. The most important factors affecting a value of resistivity of soil are humidity and temperature. During the year due to changes in atmospheric and climate conditions moisture content in soil changes and resistivity changes consequently as well. The sharpest fluctuations in resistivity are observed in upper layers of the ground, which are frozen during the winter and dry in the summer. Measurements show that when the temperature of the air decreases from 0 to –10 °C, resistivity of the soil at depth of 0.3 m increases in 10 times, and at depth of 0.5 m it increases in 3 times.

Design of grounding devices often consider only the top layer of soil because it has a major effect on resistivity of grounding devices. To create an accurate soil map it is necessary to carry out a large amount of geological work (drilling) and determine level of groundwater bearing, as well as their total mineralization that show an amount of dissolved matter (inorganic salts, organic substances) in water that lead to a significant increase in conductivity of soils. During determination of soil structure drilling operations are not performed and an effect of groundwater on its deep layers is not taken into account in many cases. It is believed that the earth in the entire volume is homogenius and has the same resistivity at any point. As a result, calculations are simplified significantly, which leads to unreasonable overestimation of the number of designed grounding devices at the site. In fact, the soil has heterogeneous structure of alternating water-permeable layers with different porosity. Water drains quickly down to waterproof layers, which affects resistivity of soil layers significantly. The lowest level of groundwater occurs in winter, when, due to soil freezing, the ground becomes waterproof. Precipitation falls in the form of frozen water crystals, which do not melt until the warm conditions come. Highest level of groundwater is recorded in the spring, when precipitation that fell during the winter melts. Top layer of soil becomes porous. All moisture formed on surface seeps into lower rocks to a waterproof layer, which causes an increase in a level of underlying groundwater. Sandy soils (sandy loam) are water-permeable. Clay ground (loams) are water-resistant.

In fact, several different ground layers may appear on an object, having not only different density levels, but also different specific electrical resistivity, which can not be ignored during selection and design of grounding devices. Therefore, in advance to design a grounding device it is important to study a map of a geological section of ground in an area of interest.

Factors that affect a resistivity value of grounding devices were previously considered in the works [1-9].

There are methods of calculation of specific electrical resistivity of water solutions of salts and rocks given in works [1]. They show a decrease in specific resistivity of soil with increase in concentration of solution ions and chemical composition of dissolved salts. Rocks conduct an electric current mainly due to the presence of water solutions of salts in their pore space. A porosity coefficient is set for non-clay rocks. It takes into account amount and nature of water distributed in the rock. For clay rocks electrical conductivity is determined both by water and surface conductivity of clay particles, in particular by hydration film covering their surface. Surface conductivity coefficient helps to count the effect of surface conductivity of clays on relative resistivity.

The article [2] deals with problems that arise in operation of grounding installations of communication facilities, connected with changes both in temperature, moisture of medium that surrounds grounding devices, and with amplitude, frequency and shape of current flowing through the ground. Change in temperature and moisture and use of substances applied to surrounding ground to reduce resistivity cause problems with concentration of ions in a solution and need for their periodic renewal, as well as with a corrosion of groundig devices.

There is a description of device for vertical electrical sounding of the earth given in the work [3]. It increases accuracy of measurement in places with local surface inclusions that have specific electrical resistivity different from earth's one.

In the article [4] authors analyze errors in calculation of resistivity of grounding devices caused by imperfections of existing computational algorithms. There are empirical formulas for grounding devices located in a multilayered earth presented to bring multilayered earth to a homogeneous one. Formulas represent generalization of results of calculations performed with help of special programs.

Depth of sounding in a two-layer ground was determined in the paper [5]. The optimum depth of sounding equal to two diagonals of a grounding device is obtained. It is noted that depth of sounding can be higher but accuracy of calculations increases just by only a few percent.

Accuracy of calculations of grounding devices can be increased significantly if heterogeneity of earth is considered. At the same time its design becomes cheaper. Nowdays, the method of calculation of grounding devices is applied. According to the method earth has two layers such as upper and lower layers, each having its own specific resistivity ρ_1 and ρ_2 and thickness h_1 and h_2 [5, 10-13].

In this paper calculations used an assumption that the earth which contains an electrode is an infinite half-space consisting of a random number of n layers. Thickness of each layer is finite. Within each i layer resistivity of the earth is constant and equal to ρ_i. A surface of the earth and interfaces between the layers are horizontal [10].

Configuration of grounding devices is selected based on a possibility of its application in a specific object. Vertical grounding electrodes are most often used during construction. That is caused by the fact that it is difficult to drown horizontal electrodes deeply. Resistivity of such electrodes at shallow depth is increased significantly in winter because an upper layer of dround is frosen. It is much more efficient to use as a grounding device a deep electrode (usually single) in a form of a rod or a steel pipe placed in a hole drilled in the ground. Large length of an electrode provides a high contact between the surface and ground (favorable conditions for transition of current to ground appear). The deeper a grounding device the lower specific electrical resistivity layers are achieved [10, 11, 13, 14].

Initially resistivity of a single grounding device was calculated by a simplified technique (homogeneous ground, over a top layer) according to the formula for a vertical grounding device

$$R = \frac{\rho}{2\pi l}\left(\ln\frac{2l}{d} + \frac{1}{2}\ln\frac{4t+l}{4t-l}\right), \quad (1)$$

where ρ – specific electrical resistivity, Ohm·m; l – length of grounding device, m; d – diameter of vertical grounding device (in accordance with a table 1.7.4 of Regulations on electrical equipment installation «Smallest sizes of grounding devices and grounding conductors laid in the ground», $d > 12$ mm), $d = 0{,}02$ m; $t = t_0 + 0.5l$, where t – distance from the ground to middle of the rod, t_0 – burial depth of a grounding device [10].

Change of the earth from multiple-layer to double one is done through assignment of layers of high values of $\rho_{h,\text{calc}}$ to an upper layer and layers that have low values of $\rho_{h,\text{calc}}$ to a lower layer. Wherein, calculated specific resistivities of upper and lower layers of the two-layer earth $\rho_{1,\text{calc}}$ and $\rho_{2,\text{calc}}$, Ohm·m, are determined by a formula

$$\rho_{1\text{calc}} = \frac{h_1 + h_2 + \ldots + h_k}{h_1/\rho_1 + h_2/\rho_2 + \ldots + h_k/\rho_k}. \quad (2)$$

$$\rho_{2\text{calc}} = \frac{h_{k+1} + h_{k+2} + \ldots + h_n}{h_{k+1}/\rho_{k+1} + h_{k+2}/\rho_{k+2} + \ldots + h_n/\rho_n}. \quad (3)$$

Here indexes from 1 to k represent numbers of layers, assigned to an upper layer of double layer earth. Indexes from (k + 1) to n represent layers assigned to a lower layer.

Deriving of the double layer earth to a single one is done by using a formula

$$\rho_e = \frac{l}{\Delta l_1/\rho_1 + \Delta l_2/\rho_2}, \quad (4)$$

where Δl_1, Δl_2 – lengths of electrode's parts in the upper and lower layers respectively, ρ_1, ρ_2 – equivalent specific resistivities of upper and lower layers [10].

Description of southern grounds of Perm region

In terms of geological structure the region is divided into two unequal in area parts such as large western part Preduralie that is characterized by platform occurrence of Paleozoic and Mesozoic deposits of different genesis and thickness and small part Ural represented by intensively dislocated rocks of Paleozoic and Proterozoic eras. Cenozoic formations are represented mainly by unconsolidated rocks of the Quaternary continental system and very small "areas" of Neogene age deposits [15-17].

In a northern part of Perm region glacial deposits of Middle Pleistocene are spread fragmentary (basins of the rivers Kosa, Urolki, Kondas). They are represented by loams, clays, sandy loams which composed the Dnieper moraine. Sandstone, quartzite, flint, shale, limestone, dolomite, rarely metamorphic and igneous rocks of Ural and Kola origin are found in composition of boulder-pebble material. The feature of glacial deposits is their high density and heterogeneity of a composition. Rock thickness is 3-5 m.

Deluvial and deluvial-solifluction deposits, that represent plumes unconsolidated rocks are widespread in central and southern parts of plain of Kama region. Due to origin of main bottom rocks composition of deluvial deposits vary from sand and gravel (products of destruction of sandstones and conglomerates) to clays and loam (products of destruction of mudstones, siltstones, dolomites etc.). There are interlayers of buried ancient soils and (or) rubble often observed in middle and upper parts of a section in loam. Sediment thickness is up to 15 m [15, 16, 18].

A ground structure for northern and southern parts of Perm region was selected to calculate resistivity of a single grounding device (Table 1).

Values of specific electrical resistivities are selected in accordance with recommended values of specific electrical resistivities of upper layer of the earth (up to depth of 50 m) [11, Table 3.7].

Table 1

Ground structure of Perm region

Layer	Composition	h, m	ρ, Ohm·m
Northern part			
Upper	Sand	1	600
	Loam	2	300
Lower	Clay loam	1	100
	Clay	3	40
	Sandstone	10	1000
Southern part			
Upper	Clay loam	2	100
	Sand	1	300
	Clay	1	40
	Sand	1	200
	Clay	1	40
Lower	Unconsolidated limestone	10	300

In a simplified technique resistivity of grounding device is calculated for an upper layer with $\rho_{equiv} = 600$ Ohm·m for the north and 100 Ohm·m for the south.

Deviation of resistance of a single vertical grounding device is calculated by the formula

$$\theta = \frac{R_{simp} - R_{comp}}{R_{simp}} 100\,\%, \qquad (5)$$

where R_{comp} – resistivity of grounding device, calculated from resistivities of an upper and lower layers, Ohm; R_{simp} – grounding resistivity, calculated from an upper layer of ground, Ohm.

Fig. 1 shows functions of resistivity of vertical grounding device versus its length, calculated for the northern and southern parts of Perm region by a simplified (over an upper layer) and a complex technique (on upper and lower layers of the ground).

Presented graphs show significant deviations (40-87 %) of resistivity from real values for the northern part of Perm region and much smaller deviations (6-20 %) for the southern one. That on the one hand is caused by the fact that layering and ground characteristics were neglected during calculation of resistivity of grounding devices, on the other hand by use of simplified calculation methods. Therefore, simplified methods for calculating resistivity of a grounding device over an upper layer of ground can be used with sufficient degree of reliability for southern part of the region and are unacceptable for northern part of the region.

There are in the eastern part of the region mountain range Ural Mountains. Those have a border with the Russian platform. Burrial of the crystalline basement occurs down to depth of 6-8 km (in the center and down to 2-3 km on the western distant part of the region). The Ural is different to fore Urals by release of dislocated, crushed into folds rocks. Their age varies from the Upper Proterozoic to the Lower Permian. The lower Proterozoic is represented by quartzites, shales, quartz porphyries, clay shales, sandstones, limestones, dolomites, hematite shales. Sediments have thickness over 6000 m. The second important influence of the Urals on formation of the eastern margin of the Russian platform is the fact that unconsolidated material has Ural origin. That material represents a sedimentary cover [15].

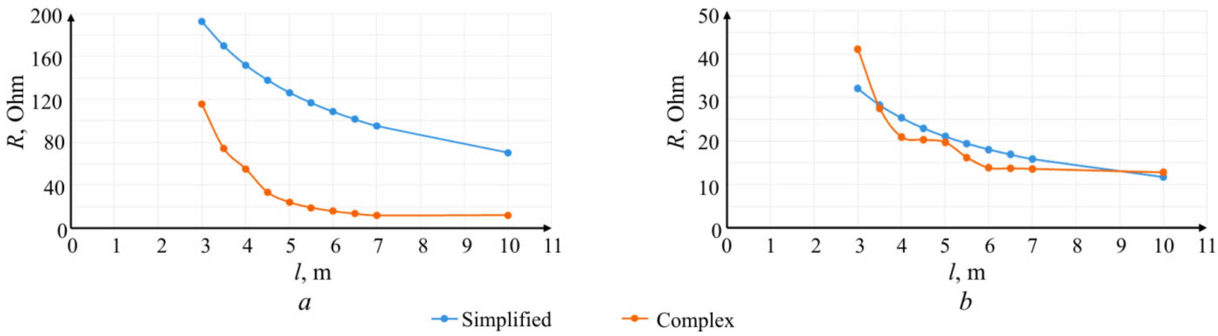


Figure 1. Function of resistivity of grounding device versus its length, calculated for northern (*a*) and southern (*b*) parts of Perm region

Thus, there are rocks in the earth in the eastern part of the region that have high resistivity. The lower ground layers (rock grounds) have a higher resistivity, which must be taken into account.

The western part of Perm region (80 % of territory) is located on the margin of the East European Plain, where low and flat terrain prevails. There is no layering, therefore, simplified methods for calculating resistivity of grounding devices for an upper layer of the ground can be used [15].

Specific ground resistivity, taking into account seasonal climate coefficient

Specific resistivity of upper layers of the earth fluctuates during the year due to changes in weather conditions, resulting in a change in soil temperature, moisture of content and salts etc. Thickness of a layer of land subject to seasonal changes is called the seasonal variation layer and is denoted by h_s. A top layer is exposed to weather conditions and its specific resistivity ρ_1 has significant seasonal fluctuations, which must be taken into account when designing grounding devices. Typically, reduction of resistance in ground occurs in spring and autumn months, when the moisture content in the soil increases. Ground resistivity increases in winter and summer due to freezing and evaporation of moisture. It is established that in order to ensure electrical safety conditions when designing a grounding device, it is necessary to take the greatest possible resistivity during a year [5].

The formula for the calculated value of resistivity for a homogeneous earth

$$\rho_{calc} = \rho_{ground} \cdot \psi, \qquad (6)$$

where ρ_{ground} – ground specific resistivity, obtained in the references; ψ – seasonal climate coefficient for a given location, which depends on the average multi-year lowest temperature (January) and the average multi-year highest temperature (July).
For the heterogenious earth there are layers that lie within thickness of the seasonal variation layer h_s, m (ρ_{calc} varies only in this zone) that are under the influence of weather conditions.

The seasonal climate coefficient for the city of Solikamsk in the north of the Perm region was determined. The average multy-year lowest temperature of January is –19.7 °C. The average multy-year highest temperature of July is 17.8 °C.

Thus, Solikamsk can be placed to the first climate zone. For electrodes with a length of 3.0-4.5 m ψ = 1.65; for 5 m – 1,35. Seasonal layer thickness $h_s = 2.2$ m.

A climate coefficient of seasonality for the city of Chernushka in the south of Perm region was determined. The average multy-year lowest temperature of January is –19.1 °C. The average multy-year highest temperature of July is 24.4 °C. Thus, the city Chernushka can be placed to the second climate zone. For electrodes with a length of 3.0-4.5 m ψ = 1.45; for 5 m – 1,25. Seasonal layer thickness $h_s = 2.0$ m [19, 20].

When a two-layer earth is inroduced ψ is considered as

$$\rho_e = \frac{l}{\frac{\Delta l_1}{\rho_1 \cdot \psi} + \frac{\Delta l_2}{\rho_2}}, \quad (7)$$

where ψ affects an equivalent resistivity of the upper layer only.

In a simplified procedure, resistivity of grounding surface is calculated for the upper layer: for the north with a length of the grounding device of up to 5 m $\rho_{equiv} = 990$ Ohm·m, with a length of grounding device more than 5 m $\rho_{equiv} = 810$ Ohm·m. For the south with length of grounding device of up to 5 m $\rho_{equiv} = 145$ Oh·m, with a length of a grounding device more than 5 m – 125 Oh·m.

The deviation of resistivity of a single vertical grounding device is calculated by formula (5). The length of the grounding surface varied from 3 to 10 m.

Figure 2 shows graphs with functions of resistance of vertical grounding devices versus its length, calculated for the northern and southern parts of Perm region by a complex procedure (for the upper and lower layers of ground), with no climate coefficient considered and with considered one.

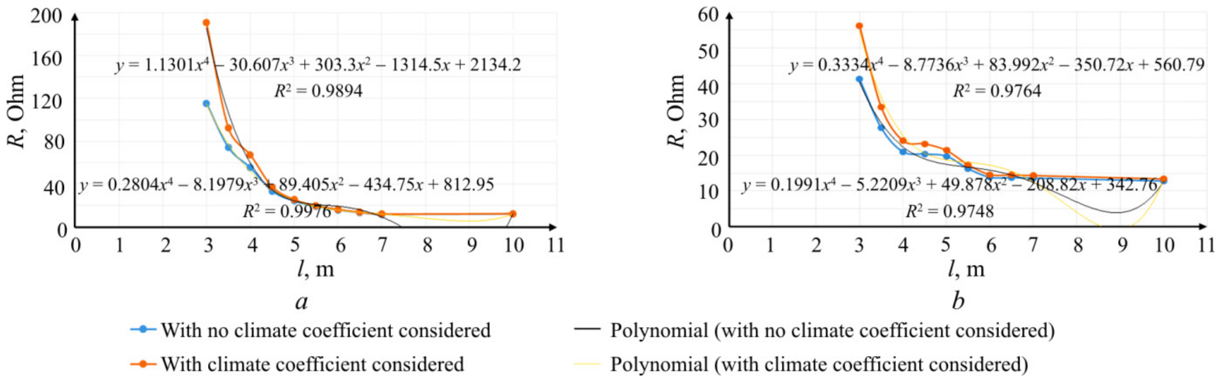


Fig. 2. Function of resistivities of grounding device versus its length, calculated for the northern (*a*) and southern (*b*) parts of Perm region, taking into account a climate coefficient

Deviation of resistivity of a single vertical grounding device, taking into account a season climate coefficient is calculated by formula

$$\theta = \frac{R_{(\psi)} - R_0}{R_{(\psi)}} 100\,\%, \quad (8)$$

where R_0 – calculated resistivity of grounding device with no climate coefficient considered; $R_{(\psi)}$ – calculated resistivity of grounding device with climate coefficient considered.

Thus, resistivity of a grounding device increases when seasonal climate coefficient is considered for the north by 21 % and for the south by 17.3 % (Table 2). Since only the upper layer of the ground is subject to seasonal changes the higher the length of vertical grounding device the less effect on equivalent resistivity of a grounding device has a climate coefficient.

Consideration of the effect of groundwater on specific ground resistivity and resistivity of a grounding device

Mineral deposits of Perm region are very rich in groundwater, which is facilitated by a geological structure of the region. Interlayering of aquifers and water-resistant layers and significant dissections of landscape provide replenishment of underground water reserves. Underground waters are the only source of rivers' supply in winter and during droughty summer periods. A share of underground water is 20-25 % in annual runoff of rivers and can be up to 30-40 % in karst. Therefore, consideration of groundwater is very important in design of grounding devices in the Perm region [15].

Table 2

Deviation of resistivity R of a grounding device with and with no season climate coefficient considered, %, calculated using simplified and complex methods

l, m	North of the region		South of the region	
	simplified	complex	simplified	complex
3	39.4	39.4	31.0	26.6
3.5	39.4	19.7	31.0	17.3
4	39.4	17.9	31.0	12.8
4.5	39.4	10.6	31.0	12.2
5	25.9	5.0	20.0	7.5
5.5	25.9	3.9	20.0	6.1
6	25.9	3.2	20.0	5.1
6.5	25.9	2.7	20.0	5.0
7	25.9	2.3	20.0	4.9
10	25.9	2.2	20.0	4.4
Mean value	31.3	10.7	24.4	10.2

Western and central parts of the region represent a hill plain, which gradually increases in the eastern and southern directions. The plain part of Perm region has a height of mainly 200 to 400 m above sea level. Rocks that form aquiferous and complexes contain fractured karst and fracture groundwater and are generally characterized by relatively low water availability. Carbonate complexes of Iren and Solikamsk suites are widely distributed within Ufa and Solikamsk valleys.

There are in the north among fractured Lower Permian rocks sandstones and limestones that have the bigest amount of water which comes to the surface of valleys of rivers and cloughs by a large number of upstream and downstream sources. Depth of water burrial is 5-10 m.

There is in the very south of the region a complex of deposits of the Upper Pliocene and Pleistocene spread on watersheds of the rivers Kama and Buja and in the valley of the Piz river. A complex is represented by clay and sandy pebble sediments of lake and alluvial genesis. Pebbles, sand, sandy loam are water-bearing rocks. Burrial depth of groundwater is from 0.5 to 5.0 m [15, 18].

Special conditions of burrial of groundwater in unconsolidated rocks make several physical properties of the ground the most important. Those properties such as porosity, moisture capacity, capillary properties and water permeability influence specific electrical resistivity. Most layers of the ground have a porous structure. Porosity of rocks is presence of pores in it (voids such as pores, caverns, cracks). Porosity characterizes an ability of rock to contain liquids and gases.

Specific electrical resistivity of water-bearing rocks can be compared with a water content using the empirical formula

$$\rho = a \cdot \rho_w \cdot \Phi^{-m} \cdot S^{-n},$$

where ρ_w – specific electrical resistivity of water contained in the rock; Φ – value of rock porosity; S – a share of threshold volume filled with water; n – porosity (an empirical coefficient that varies); a, m – empirical parameters taken from the Table 3.4 [11]. The parameter m varies from 1.3 for unconsolidated sand to 2.5 for a tightly cemented granular rock. Ground porosity is not a constant value and depends on density of its compaction. Porosity of a particular rock varies from 6 to 52 % for sand, from 3.5 to 29 % for sandstone, from 5 to 33 % for limestone, from 6 to 50 % for clay [21].

Influence of rock porosity on a specific electrical resistivity of the ground was studied for various areas of Perm region on example of such rocks as sand, sandstone and limestone. Values of ground porosity Φ and coefficients a, m for water-containing grounds are given in the Table 3 [11, Table 3.4].

Table 3

Values of porosity Φ and coefficients of a, m for water-containing rocks

Rock	Φ	a	m
Sand	0.25	0.62	2.15
Sandstone	0.14	0.62	2.1
Limestone	0.13	2.2	1.65

A specific electrical resistivity of water varies from 30 to 100 Ohm·m depending on the degree of mineralization. For calculation an average value of 50 Ohm·m is used.

In order to determine pore volume filled with water it is necessary to use the methodology presented in [22].

If the porosity is set as $V_{\text{gr}} = 200$ m^3 (for example, during design of a grounding device with an electrode located along the perimeter of the building) then necessary calculations for an analysis of the effect of rock porosity on a specific electric resistivity of grounds are done.

ρ_s – a ratio of mass of dry ground (excluding the mass of water in its pores) to the volume of a solid part of this ground; is assumed according to the Table 1.2 [22] for sand $\rho_s = 2660$ kg/m^3 , for sandstone $\rho_s = 2320$ kg/m^3, for limestone $\rho_s = 2600$ kg/m^3.

ρ_w – a ratio of mass of moist ground (excluding the mass of water in its pores) to the volume of the ground; for sandstone $\rho_w = 1920$ kg/m^3, for sand $\rho_w = 1450$ kg/m^3, for limestone $\rho_w = 1400$ kg/m^3.

Density of dry ground (a ratio of dry ground weight (excluding mass of water in its pores) to volume occupied by this ground (including pores in this ground) is determined by the formula

$$\rho_d = (1-n)\rho_S.$$

Volume of solid part of ground is found from the formula

$$V_{\text{sol}} = (1-n)V_{\text{gr}}.$$

Volume of wet part of soil is calculated by the formula

$$V_{\text{wet}} = V_{\text{gr}} - V_{\text{sol}},$$

Mass of dry part of ground is

$$m_{\text{dry.gr}} = \rho_d \cdot V_{\text{sol}},$$

mass of moist part of ground is

$$m_{\text{mois.gr}} = \rho_w \cdot V_{\text{mois}}.$$

Mass of ground equals to

$$m = m_{\text{dry.gr}} + m_{\text{mois.gr}}.$$

Equivalent ground resistivity

$$\rho_{\text{eq}} = \frac{V_{\text{sol}}}{m}.$$

Moisture content of ground is defined as

$$w = \frac{\rho_{\text{eq}} - \rho_d}{\rho_d}.$$

Porosity cannot provide a sufficient enough description of a ground state. Therefore, an index of ground density is used in calculations such as a coefficient of porosity. A coefficient of porosity represents a ratio of pore volume in a sample to the volume occupied by its solid particles (skeleton): $e = \frac{n}{100-n}$.

A ratio of natural moisture content of the ground W to moisture corresponding to full pores with water is a coefficient of water content

$$S_r = \frac{w \cdot \rho_s}{e \cdot \rho_w}.$$

Total moisture capacity of ground is determined by the formula

$$w_0 = \frac{e \cdot \rho_w}{\rho_s}.$$

Porosity values and an additional coefficient of porosity determine structure of ground. A characteristic of soil moisture is its weight porosity. That is a state when pores are completely filled with water. Porosity, which is not calculated parameter, is used in calculations as an important additional value [11].

If the volume of solid part of ground changes, then a share of pore volume, filled with water, changes. Ground volume maintains the same. Calculation of specific electrical resistivity of sand with rock porosity considered is presented in the Table 4.

Calculations for sandstone and limestone are performed in the range of their porosity variation in the same way.

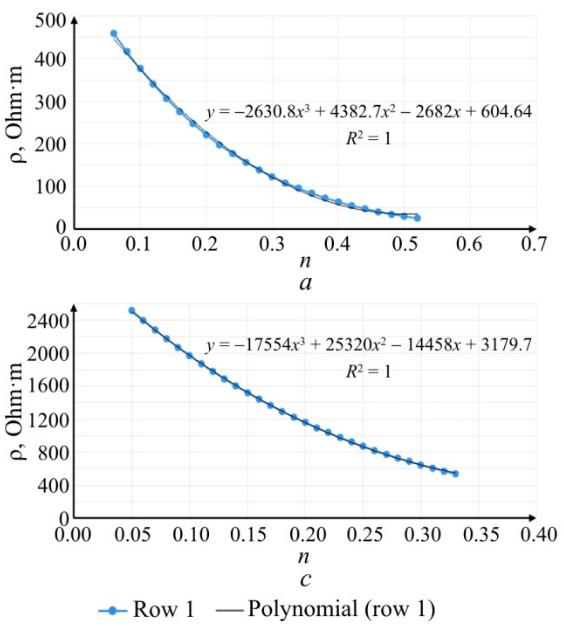
Fig. 3 shows functions of specific electrical resistivities of ground (sand, limestone and sandstone) on its porosity.

Thus, according to the graphs given in Fig. 3, specific electric resistivities vary within wide ranges depending on different porosity values (Table 5).

Table 4

Calculation of specific electrical resistivity of sand with porosity influence considered

n	ρ_d, kg/m^3	V_{sol}, m^3	$m_{dry.gr}$, kg	m, kg	ρ_{eq}	w	e	S_r	ρ, Ohm·m
0.06	2500.4	188	470075.2	493115.2	2623.0	0.05	0.0006	113.1	459.8
0.08	2447.2	184	450284.8	481004.8	2614.2	0.07	0.0008	118.1	416.9
0.1	2394	180	430920	469320	2607.3	0.09	0.0010	123.3	377.3
0.12	2340.8	176	411980.8	458060.8	2602.6	0.11	0.0012	129.0	340.8
0.14	2287.6	172	393467.2	447227.2	2600.2	0.14	0.0014	135.0	307.3
0.16	2234.4	168	375379.2	436819.2	2600.1	0.16	0.0016	141.5	276.5
0.18	2181.2	164	357716.8	426836.8	2602.7	0.19	0.0018	148.5	248.3
0.2	2128	160	340480	417280	2608.0	0.23	0.0020	155.9	222.4
0.22	2074.8	156	323668.8	408148.8	2616.3	0.26	0.0022	164.0	198.8
0.24	2021.6	152	307283.2	399443.2	2627.9	0.30	0.0024	172.7	177.4
0.26	1968.4	148	291323.2	391163.2	2643.0	0.34	0.0026	182.1	157.8
0.28	1915.2	144	275788.8	383308.8	2661.9	0.39	0.0028	192.4	140.0
0.3	1862	140	260680	375880	2684.9	0.44	0.0030	203.5	123.9
0.32	1808.8	136	245996.8	368876.8	2712.3	0.50	0.0032	215.6	109.4
0.34	1755.6	132	231739.2	362299.2	2744.7	0.56	0.0034	228.8	96.3
0.36	1702.4	128	217907.2	356147.2	2782.4	0.63	0.0036	243.3	84.5
0.38	1649.2	124	204500.8	350420.8	2826.0	0.71	0.0038	259.2	73.9
0.4	1596	120	191520	345120	2876.0	0.80	0.0040	276.7	64.4
0.42	1542.8	116	178964.8	340244.8	2933.1	0.90	0.0042	296.0	56.0
0.44	1489.6	112	166835.2	335795.2	2998.2	1.01	0.0044	317.5	48.4
0.46	1436.4	108	155131.2	331771.2	3072.0	1.14	0.0046	341.4	41.7
0.48	1383.2	104	143852.8	328172.8	3155.5	1.28	0.0048	368.0	35.8
0.5	1330	100	133000	325000	3250.0	1.44	0.0050	398.0	30.6
0.52	1276.8	96	122572.8	322252.8	3356.8	1.63	0.0052	431.8	26.0



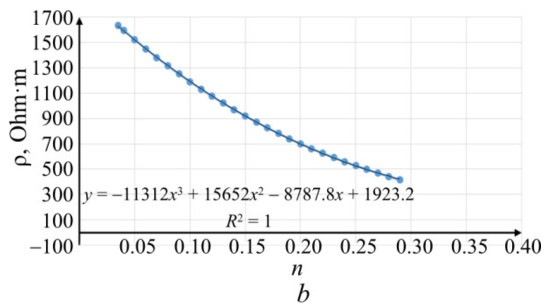


Fig. 3. Functions of specific resistivity of ground versus porosity: *a* – sand; *b* – sandstone; *c* – limestone

These graphs are convenient to use during design of grounding devices. For example, for large values of ground porosity, its specific electrical resistivity is sharply reduced due to the fact that pores can be filled with water and their conductivity can be increased.

If porosity values varied from minimum to maximum, specific electrical resistivity of sand decreased in the greatest number of times (in 17.68 times), while specific electrical resistivity of limestone increased by the maximum value (1982.8 Ohm·m).

Table 5

Limits of change of specific electrical resistivity of ground, depending on its porosity

Rock	n_{min}, %	n_{max}, %	ρ_{max}, Ohm·m	ρ_{min}, Ohm·m	Deviation in value, Ohm·m	Deviation, times
Sand	6	52	459.8	26.0	433.8	17.68
Sandstone	3.5	29	1634.6	415.5	1219.1	3.93
Limestone	5	33	2518.7	535.9	1982.8	4.69

When oil fills rock pores, conductivity of rocks is significantly reduced and its specific resistivity is increased. That leads to significant increase in resistance of grounding devices if there is high porosity.

Conclusion

Based on studies carried out, it is shown that design of grounding devices has to consider basic properties of grounds such as layering, porosity and climate zone, in which a grounding device is designed. Application of simplified techniques for design of grounding devices leads to significant deviations in calculated values of resistivities from real ones.

It is found that the most efficient calculation of resistivity of grounding devices is a calculation that considers multilayer ground, changes in weather conditions and depth of groundwater burrial. It is shown that design of ground devices has to consider season climate coefficient so that the resistivity of a grounding device would not exceed permissible values under worst conditions. Permissible values are regulated by normative documents. Herewith electrical safety conditions (values of contact voltage and step voltage are within permissible ones) have to be ensured.

The work shows ground porosity influences a value of specific electrical resistivity of the rock significantly. If mineralization is high, conductivity of rocks increases due to increase in concentration of solution ions and chemical composition of dissolved salts. Electrical resistivity of rocks change in certain range. Limits of a range can change more than in 17 times (for sand) depending on rock porosity. Therefore, before design of grounding devices it is necessary to know climate conditions of an area and structure of grounds of a given terrain with depth at which groundwater is burried.

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