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Application of the multilayer soil equivalence method in determining the normalized parameters of the grounding system

Introduction. *Normalized parameters of the grounding system, such as touch voltage and resistance, are critically important for ensuring electrical safety and reliability of power plants and substations. The complexity of the multi-layered soil structure makes it difficult to determine mentioned parameters. This is due to the fact that real soils on the territory of energy facilities of Ukraine have three or more layers, and the specified parameters are determined by software with two-layer calculation models. Therefore, the need to provide multilayer geoelectric structures into equivalence two-layer models for practical application is an urgent task.* ***Goal.*** *Determination of the application limits of the multilayer soils equivalence method based on the calculating results analysis of the grounding system normalized parameters.* ***Methodology.*** *The study considered a three-layer model for four soil types (A, H, Q, K) common in Ukraine. The calculations were performed using the LiGro software package, which is based on the method of integro-differential equations, applied to the analytical solution of the problem of the electric field potential of a point current source in a three-layer conducting half-space. As a criterion for the possibility of applying the equivalence method, a relative error value of 10 % was chosen when determining the normalized parameters of a grounding system of the given topology and soil type. When determining the error, the calculation results in the original three-layer soil structure for the given topology of the grounding system were taken as the true value.* ***The results*** *show that the effectiveness of equivalent technique significantly depends on the type of soil and the area of the grounding system. In particular, for soil type A, replacing the upper and middle layers with the equivalent first layer (the lower layer with the second) provides a smaller error in the calculations of the grounding resistance than representing the upper layer as the first, and the middle and lower layers as the second equivalent layer. At the same time, there is a tendency for the error to decrease with increasing area of the object: from 225 m*^{2} *to 14400 m*^{2}*, for the first case, the error decreased from –14.6 % to –2.6 %, and for the second case, it changed from –9.3 % to 14.6 %, respectively.* ***Originality.*** *For the first time, the results of the methodical error evaluation of the equivalence techniques of multilayered soils of different types when calculating the normalized parameters of grounding system are presented.* ***Practical value.*** *Determination of the conditions and limits of the use of the equivalence method when calculating the normalized parameters of grounding system by software complexes can be used in the design of new or reconstruction of existing energy facilities of Ukraine.* References 20, tables 5, figures 4.

Key words: **grounding system, touch voltage, resistance of grounding, method of equivalence, multi-layered soil.**

Вступ. *Нормовані параметри заземлювального пристрою, такі як напруга дотику та опір, є критично важливими для забезпечення електричної безпеки та надійності роботи електростанцій та підстанцій. Складність багатошарової структури ґрунту створює проблеми для визначення вказаних параметрів. Це обумовлено тим, що реальні ґрунти на території енергооб'єктів України мають три і більше шарів, а нормовані параметри визначаються програмними засобами з двошаровими розрахунковими моделями. Тому необхідність еквівалентування багатошарових геоелектричних структур у двошарові моделі для практичного застосування є актуальною задачею.* ***Мета.*** *Визначення меж застосування методу еквівалентування багатошарових ґрунтів на основі аналізу результатів розрахунку нормованих параметрів заземлювального пристрою.* ***Методологія.*** *У дослідженні розглянуто тришарову модель для чотирьох типів ґрунту (A, H, Q, K), поширених в Україні. Розрахунки виконано за допомогою програмного комплексу LiGro, який базується на методі інтегро-диференційних рівнянь, застосованому для аналітичного вирішення задачі про потенціал електричного поля точкового джерела струму в тришаровому провідному напівпросторі. В якості критерію можливості застосування методу еквівалентування обрано величну відносної похибки в 10 % при визначенні нормованих параметрів заземлювального пристрою заданої топології та типу ґрунту. При визначенні похибки за істинне значення приймались результати розрахунку у вихідній тришаровій структурі ґрунту для заданої топології заземлювального пристрою.* ***Результати*** *демонструють, що ефективність методу еквівалентування суттєво залежить від типу ґрунту та площі системи заземлення. Зокрема, для ґрунту типу A заміна верхнього та середнього шару еквівалентним першим шаром (нижнього – другим), забезпечує меншу похибку розрахунків опору заземлення, ніж представлення верхнього шару в якості першого, а середнього та нижнього – другого. При цьому спостерігається тенденція до зменшення похибки від –14,6 % до –2,6 % зі зростанням площі об'єкту від 225 м*^{2} *до 14400 м*^{2}*.* ***Оригінальність.*** *Вперше представлено результати оцінки похибки методу еквівалентування багатошарових ґрунтів різних типів при розрахунку нормованих параметрів заземлювальних пристроїв.* ***Практична цінність.*** *Визначення умов та меж застосування методу еквівалентування при розрахунку нормованих параметрів заземлювальних пристроїв програмними комплексами може бути використано при проєктуванні нових або реконструкції існуючих енергооб'єктів України.* Бібл. 20, табл. 5, рис. 4.

Ключові слова: **заземлювальний пристрій, напруга дотику, опір заземлювального пристрою, метод еквівалентування, багатошаровий ґрунт.**

Introduction. Calculation of the normalized parameters of grounding devices (GDs) of power plants and substations, namely GD resistance, GD voltage and touch voltage, is an important scientific and practical task both from the point of view of designing new energy facilities [1–3] and operating existing ones [4]. The initial data for performing such calculations are the single-phase ground fault current, the operating time of the main and backup protection, GD topology [5], the material and cross-section of the grounding conductors, the resistance of the base [6] and the electrophysical characteristics of the soil [7]. The latter factor is practically independent of human influence and cannot be changed during operation.

In common software packages for modelling electromagnetic processes in GDs [8–13], a two-layer soil model with a separation boundary parallel to the ground surface is used. Based on the fact that, according to the results of the analysis of 612 soundings, more than 80 % of soils in the locations of energy facilities in Ukraine have three or more layers [7], there is a need to reduce the existing structure to a two-layer one. Usually, the equivalence method is used for this [12–18]. Its idea is that a model with such characteristics of the geoelectric structure of the earth is considered equivalent, under which the grounding conductor will have the same values of electrical parameters as in the original multilayer structure.

To reduce the multilayer geoelectric structure to equivalent, the total transverse (normal) and longitudinal (tangential) conductivities are determined when currents flow in the corresponding directions in a rectangular soil column of height h_{Σ}, with a base in the form of a square with a side of a known size (for example, a = 1 m). The expressions for determining the equivalent resistivity ρ_e (1) and the equivalent layer thickness h_e (2) have the form [7, 14, 15]:

$$\rho_e = \sqrt{\sum_{i=1}^{m}(h_i \cdot \rho_i) \times \left(\sum_{i=1}^{m} \frac{h_i}{\rho_i}\right)^{-1}}; \quad (1)$$

$$h_e = \sqrt{\sum_{i=1}^{m}(h_i \cdot \rho_i) \times \sum_{i=1}^{m} \frac{h_i}{\rho_i}}, \quad (2)$$

where ρ_i and h_i are the resistivity and thickness of the i-th layer, m is the number of equivalent layers.

In general, three methods (see section 2.3.2 [3]) of applying the equivalence method [7] have become widespread in practice:

1. Method No. 1 – the upper layer of a real geoelectric structure is considered as the first layer of an equivalent two-layer one, and the following layers are equivalent to the second (it is believed that this method allows to determine the potential distribution on the soil surface and the touch voltage with the smallest errors).

2. Method No. 2 – all upper layers of the real structure are represented as the first layer of an equivalent geoelectric structure, and the lower one is the second layer (this method is usually used when calculating the resistance and potential on the ground).

3. Method No. 3 – all upper layers of the real structure before the grounding conductor and additional 0.1–0.2 m are represented as the first layer of the equivalent geoelectric structure, and the lower ones (or those that are lower relative to the grounding conductor elements, other layers) are represented as the second layer.

The first and second methods are obtained on the basis of the physical meaning of the normalized parameters: the ratio of the specific electrical resistance ρ of the upper layers has the greatest influence on the value of the potential on the soil surface, and therefore on the touch (step) voltage, and the resistance and potential on the grounding conductor are more influenced by ρ of the layer in which the grounding conductor is located (see section 2.3.2 [3]). The third method has been practically applied in the Research and Design Institute «Molniya» of NTU «KhPI» on the basis of numerical calculations and comparison of experimental and calculated values.

However, in [9–15] there are no visual information and analytical and statistical data that would allow assessing the general impact of the equivalence of different types of soil (A, H, Q, K) on the results of calculating the normalized parameters. The results obtained in [4] can be considered only a preliminary analysis for a GD 5×5 m^2 area and insufficient for practical use.

Considering that the specified parameters affect the electrical safety of station and substation service personnel, as well as the reliability of equipment operation, relay protection systems and telemechanics, the study of such an impact to increase the accuracy of their determination is a relevant task.

The goal of the work is to determine the limits of application of the method of equivalence of multilayer soils based on the analysis of the results of calculating the normalized parameters of the grounding device.

Research materials. Considering that in Ukraine, in the locations of energy facilities, the vast majority of soils are three-layered, it is advisable to consider this particular geoelectric structure and the method of its equivalence. It is generally known that three-layer soils are divided into four types based on the ratio of the electrical resistivity of the layers:

- Q – ($\rho_1 > \rho_2 > \rho_3$);
- A – ($\rho_1 < \rho_2 < \rho_3$);
- H – ($\rho_1 > \rho_2 < \rho_3$);
- K – ($\rho_1 < \rho_2 > \rho_3$).

The analysis of the percentage distribution of the results of experimental soil sounding studies on the territory of energy facilities of Ukraine, carried out in [4], showed that the soil type Q is 44.43 %; A – 0.84 %; H – 31.42 %; K – 23.31 %.

To achieve the goal, as a criterion for the limits of application of the equivalence method, it is proposed to choose a value of relative error of 10 % (acceptable for solving practical problems on calculating the soil surface [6, 8, 11]) when determining the normalized parameters of the GD of a given topology and soil type. To carry out the study of the above soil types, the LiGro software package was used [17], which allows determining the normalized parameters of the GD of arbitrary complexity, located in a three-layer soil. The specified complex was created on the basis of the method of integro-differential equations, applied for analytical solution of the problem of electric field potential of a point current source in a three-layer conductive half-space, with subsequent integration of a set of point current sources in the form of an arbitrarily oriented grounding conductor.

To perform the calculations, three variants of the GD with the size of 15×15 m^2, 45×45 m^2 and 120×120 m^2 were used. The cell size in all cases is 3×3 m^2 (see Tables 1 – 4). A rod made of hot-rolled steel BSt3SP (Fe37-3FN) with diameter of 14 mm with the corresponding electromagnetic characteristics was chosen as the grounding conductor. The grounding conductor is located at a depth of 0.5 m, which meets the requirements of the regulatory document [19].

According to [7], it is advisable to consider the values at the ratio $\rho^* = \rho_i/\rho_{i+1}$ in the range [0.01; 10], which allows to cover 99.9 % of three-layer soils of Ukraine in the locations of operating energy facilities [4]. According to [4], the thickness of the layers is within $h_1 \in [0.02; 10]$ m for the first layer and $h_2 \in [0.01; 35]$ m for the second one. To perform a qualitative analysis, the average value of h_1 and h_2 was chosen [7]. The parameters of the considered initial three-layer and equivalent two-layer soil models are given in Table 1 – 4.

In this case, the average statistical values obtained in [7] are taken as the initial soil model. The equivalent two-layer ones are obtained using (1) and (2).

When performing calculations, it is assumed that the resistance of the base is 100 Ω [3], and the current of a single-phase fault to the ground is 10 kA. The calculation of the touch voltage was performed at the center (U_{tc}) and at the edge (U_{tk}) of the grounding conductor (see Tables 1 – 4). The resistance of the GD (R_G) and the voltage on the GD (U_G) were also determined. The calculation results (values of U_{tc}, U_{tk}, R_G and U_G) for a given grounding system located in soil type A are given in Table 1.

Table 1

Results of calculation of the parameters of the GD for soil type A

Parameter	Original model	Equivalent model by method:		
		No. 1	No. 2	No. 3
ρ_1, Ω·m	10	10	64,3	10
h_1, m	0,79	0,8	8,7	0,6
ρ_2, Ω·m	100	570,3	1000	510
h_2, m	5,46			
ρ_3, Ω·m	1000			
GD 15×15 m^2				
U_{tc}, V	91,81	73,43	848,60	92,82
R_G, Ω	3,61	3,94	4,13	4,40
U_G, V	36050,0	39420,0	41310,0	43990,0
U_{tk}, V	512,80	548,70	2183,00	635,60
GD 45×45 m^2				
U_{tc}, V	34,77	39,26	111,20	38,41
R_G, Ω	2,36	2,29	2,49	2,15
U_G, V	23550,0	22940,0	24940,0	21540,0
U_{tk}, V	243,50	237,60	974,10	234,30
GD 120×120 m^2				
U_{tc}, V	30,16	31,15	40,16	32,11
R_G, Ω	1,45	1,24	1,49	1,24
U_G, V	14530,0	12410,0	14910,0	12400,0
U_{tk}, V	127,70	116,20	436,30	121,60

Tables 2–4 show the results of a similar calculation for other soil types.

Table 2

Results of calculation of the parameters of the GD for soil type H

Parameter	Original model	Equivalent model by method:		
		No. 1	No. 2	No. 3
ρ_1, Ω·m	1000	1000	39,4	1000
h_1, m	0,8	0,8	21,7	0,6
ρ_2, Ω·m	10	211,5	1000	212,3
h_2, m	6,3			
ρ_3, Ω·m	1000			
GD15×15 m^2				
U_{tc}, V	24770	21300	736,10	15860
R_G, Ω	4,60	9,08	1,84	8,06
U_G, V	46000	90820	18410	80580
U_{tk}, V	25740	28340	1270	22710
GD 45×45 m^2				
U_{tc}, V	5126	4340,00	133,60	3225
R_G, Ω	1,68	2,75	1,08	2,55
U_G, V	16810	27450	10810	25470
U_{tk}, V	6270	7909	477,10	6577
GD 120×120 m^2				
U_{tc}, V	467,2	594,30	36,92	446,2
R_G, Ω	0,84	0,89	0,72	0,86
U_G, V	8290	8920	7180	8644
U_{tk}, V	1466	1958	217,30	1704

Table 3

Results of calculation of the parameters of the GD for soil type Q

Parameter	Original model	Equivalent model by method:		
		No. 1	No. 2	No. 3
ρ_1, Ω·m	1000	1000	155,54	1000
h_1, m	0,8	0,8	8,7	0,6
ρ_2, Ω·m	100	17,5	10	19,6
h_2, m	6,3			
ρ_3, Ω·m	10			
GD 15×15 m^2				
U_{tc}, V	23800	24810	2953	16380
R_G, Ω	4,81	3,77	2,89	2,53
U_G, V	48120	37660	28920	25330
U_{tk}, V	26810	25850	4793	17570
GD 45×45 m^2				
U_{tc}, V	5494	5437	812,8	530,6
R_G, Ω	1,01	0,87	0,62	0,27
U_G, V	10040	8657	6203	2680
U_{tk}, V	6127	5926	1250	935
GD 120×120 m^2				
U_{tc}, V	861,5	815	159,8	497,7
R_G, Ω	0,19	0,18	0,13	0,16
U_G, V	1852	1772	1320	1587
U_{tk}, V	1082	1095	274,1	874,2

Table 4

Results of calculation of the parameters of the GD for soil type K

Parameter	Original model	Equivalent model by method:		
		No. 1	No. 2	No. 3
ρ_1, Ω·m	10	10	253,8	10
h_1, m	0,8	0,8	21,7	0,6
ρ_2, Ω·m	1000	47,3	10	47,1
h_2, m	6,3			
ρ_3, Ω·m	10			
GD 15×15 m^2				
U_{tc}, V	84,22	159,20	4412,00	193,50
R_G, Ω	2,29	0,95	6,00	1,01
U_G, V	22890,0	9500,0	59960,0	10090,0
U_{tk}, V	538,70	432,90	7935,00	478,90
GD 45×45 m^2				
U_{tc}, V	51,27	56,47	1056,00	63,57
R_G, Ω	0,85	0,39	1,54	0,40
U_G, V	8542,0	3888,0	15350,0	4012,0
U_{tk}, V	200,80	165,50	2372,00	179,00
GD 120×120 m^2				
U_{tc}, V	34,37	33,79	220,10	34,80
R_G, Ω	0,25	0,16	0,34	0,16
U_G, V	2479,0	1626,0	3364,0	1649,0
U_{tk}, V	78,17	76,61	536,10	80,03

To analyze the data of the calculation experiments, the error in determining the normalized parameters δ using the equivalence method was considered. The true values were those obtained when calculating using the model of the GD placed in a three-layer soil. For each of the normalized parameters and the corresponding soil type, the dependence of the relative error δ on the GD area S was constructed.

Figure 1 shows the specified dependence for soil type A. Here, in Fig. 1,*a*, the dotted line indicates the family of curves for the touch voltage at the edge of the GD (U_{tk}), and the solid line indicates the touch voltage in the center of the GD (U_{tc}). The designations No. 1 – No. 3 correspond to the methods of equivalence. In Fig. 1,*b*, the solid curves correspond to the dependence $\delta(S)$ for the

GD resistance (R_G), and the dotted lines indicate the voltage on the GD (U_G).

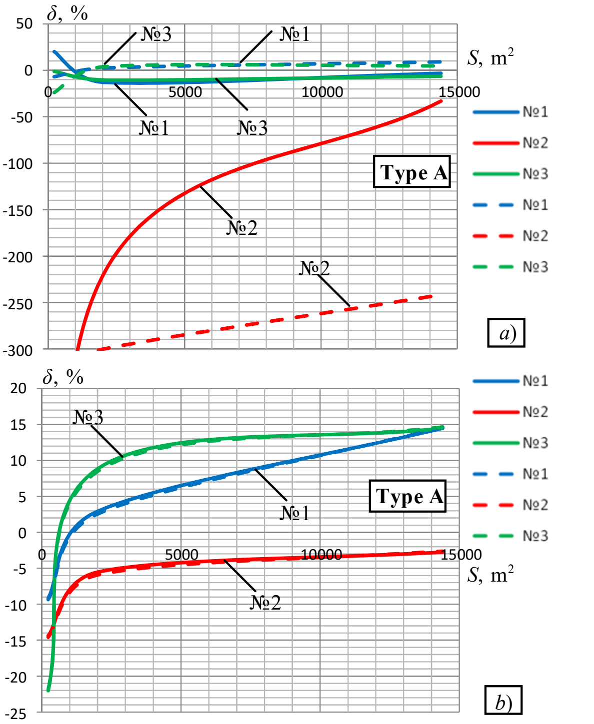

Fig. 1. Error in determining normalized parameters depending on the area of the GD and the method of equivalence of soil type A:
a – solid curve – U_{tc}; dotted curve – U_{tk};
b – solid curve – R_G; dotted curve – U_G

It should be noted that the error of more than 300 % is not shown in the graph. According to the results of modeling for soil type A, we see confirmation of the initial hypothesis – method No. 2 is quite effective for calculating the voltage on the GD and the GD resistance (the error decreases with increasing area), and methods No. 1 and No. 3 show a sufficiently high accuracy in determining the touch voltage. At the same time, in the center of the GD, method No. 3 shows the best results (error up to –10.5 %), and at the edge of the GD – method No. 1 (error up to 9 %).

Figure 2 shows similar calculation results for soil type H.

According to the results of modeling for soil type H, we see that the error in calculating the touch voltage in the center and at the edge of the GD lies in the range from –27 % to 15 % (equivalence methods No. 1 and No. 3). However, it is practically impossible to identify a specific range of application for them. For the specified type of soil, the use of the equivalence method for calculating the voltage on the GD and the GD resistance is not recommended, although the tendency for the error to decrease with increasing area remains. At the same time, contrary to the established opinion, methods No. 1 and No. 3 have the smallest error (for them, the absolute value of the error decreases from –97 % to –6 % and from –75 % to –4 %, respectively). However, in the future, it is necessary to additionally investigate their behavior with an increase in the RP area.

Figure 3 shows similar calculation results for soil type Q. The symbols are similar to Fig. 1.

According to the modeling results for soil type Q, we see that only method No. 1 can be used to calculate the touch voltage in the center and at the edge of the GD (the error lies in the range from –4.2 % to 5.6 %), the voltage on the GD and the GD resistance (the error is from 22 % to 4.3 %).

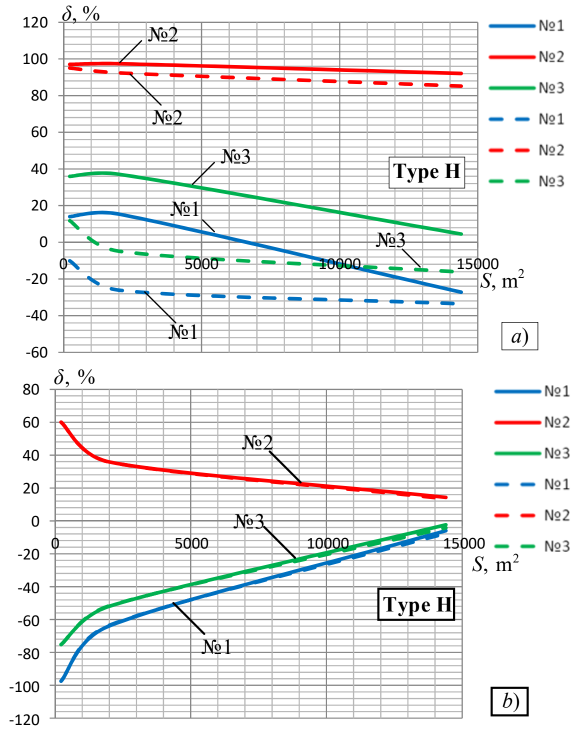

Fig. 2. Error in determining normalized parameters depending on the area of the GD and the method of equivalence of soil type H:
a – solid curve – U_{tc}; dotted curve – U_{tk};
b – solid curve – R_G; dotted curve – U_G

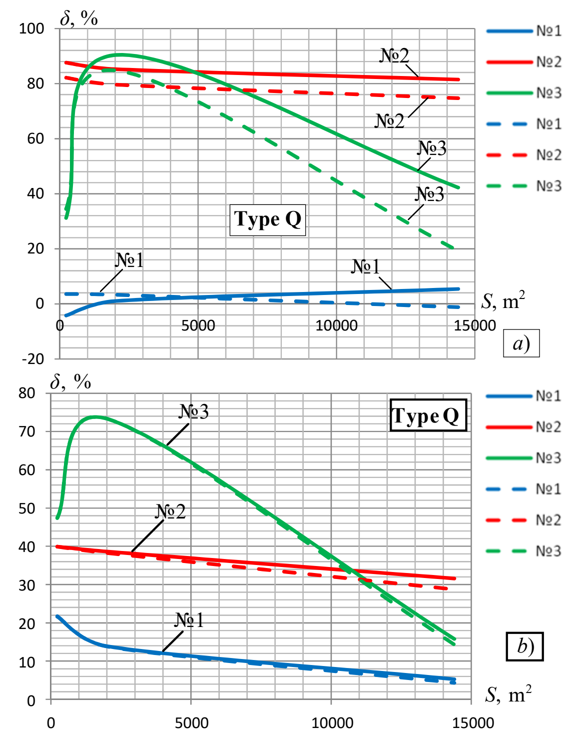

Fig. 3. Error in determining normalized parameters depending on the area of the GD and the method of equivalence of soil type Q:
a – solid curve – U_{tc}; dotted curve – U_{tk};
b – solid curve – R_G; dotted curve – U_G

Figure 4 shows similar calculation results for soil type K. The symbols are similar to Fig. 1. In Fig. 4,*a*, method No. 2 is not shown, since it gives an error of more than –500 %.

According to the simulation results for soil type K, we see that the equivalence methods No. 1 and No. 3 can be used to calculate the touch voltage in the center and at the edge of the foundation, respectively, with area of less than 2000 m^2 (the error lies in the range from –10 % to 15 %). The use of the equivalence method for calculating the voltage on the foundation and the foundation resistance is not recommended, although the tendency for the error to decrease with increasing area is also preserved.

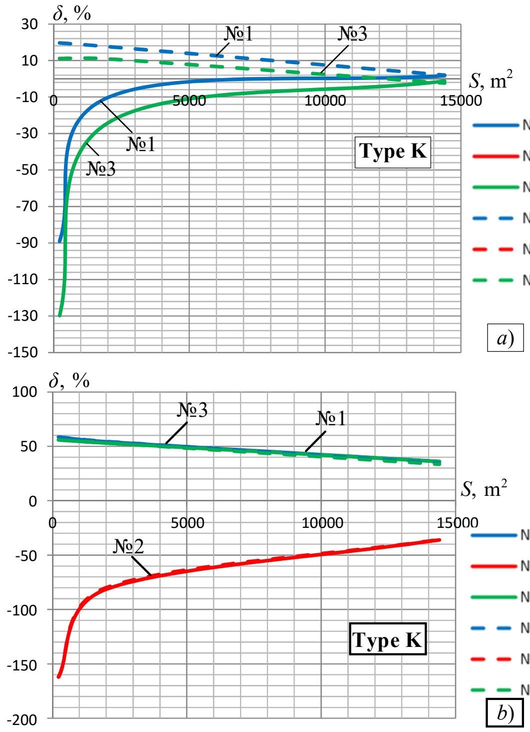

Fig. 4. Error in determining normalized parameters depending on the area of the GD and the method of equivalence of soil type K:
a – solid curve – U_{tc}; dotted curve – U_{tk};
b – solid curve – R_G; dotted curve – U_G

According to the results of the analysis of Fig. 1 – 4, we can form the following algorithm for choosing an equivalence method for calculating a certain normalized parameter of the GD depending on the type of soil (see Table 5). The principle of forming Table 5 was as follows: if for a certain type of soil when calculating one of the normalized parameters the condition

$$|\delta| \leq 10\ \% \tag{3}$$

is achieved, then the number of the corresponding equivalence method is indicated and it is recognized as acceptable for use.

If there are certain restrictions on the area of the GD for which condition (3) is achieved, then the method is accepted as conditionally acceptable, and the restrictions are given in the note. If condition (3) is not met, then the method is considered unacceptable, and Table 5 indicates «–».

The application of the proposed algorithm for selecting the equivalence method is considered on the example in Appendix 1.

Table 5

Recommendations for the algorithm for choosing the equivalence method

Soil type / GD parameter	U_{tc}	U_{tk}	R_G	U_G
Type A ($\rho_1 < \rho_2 < \rho_3$)	3	1	2*	2*
Type H ($\rho_1 > \rho_2 < \rho_3$)	–	–	–	–
Type Q ($\rho_1 > \rho_2 > \rho_3$)	1	1	–	–
Type K ($\rho_1 < \rho_2 > \rho_3$)	1**	3**	–	–

Note: * – permissible at S > 1000 m^2;
** – permissible at S > 2000 m^2.

Conclusions.

1. Based on a series of calculation experiments and analysis of the obtained values of the normalized parameters of the grounding device, it was established:

– for soil type A, methods No. 1 (the upper layer of the real geoelectric structure – the first layer of the equivalent two-layer, and the following layers are equivalent to the second) and No. 3 (all the upper layers of the real structure to the GD and an additional 0.1–0.2 m – the first layer of the equivalent structure, and the following ones – the second layer) can be used to determine the touch voltage, where method No. 3 is better for the center of the GD (error up to –10.5 %), and method No. 1 is better for the edge of the GD (error up to 9 %). Method No. 2 (the upper layers of the real structure – the first layer of the equivalent structure, and the lower one – the second layer) for calculating the voltage and resistance of the GD is allowed to be used for areas over 1000 m^2;

– for soil type H, none of the equivalence methods allows for a calculation with error of less than 10 %;

– for soil types Q and K, the equivalence method can be used only for calculating the touch voltage. In this case, for Q, the equivalence method No. 1 should be used (error from –4.2 % to 5.6 %). For type K, method No. 1 is better for the center of the GD, and method No. 3 is better for the edge of the GD with area of over 2000 m².

2. Regardless of the soil type, when determining the GD resistance and the GD voltage, in all cases there is a decrease in the error with increase in the GD area, which indicates the possibility of improving the accuracy of calculations for objects with area of over 10,000 m^2.

3. Based on the analysis of the modelling results, an algorithm for selecting the equivalence method for calculating a certain normalized GD parameter depending on the soil type was formed. The relative error within ±10 % was chosen as the acceptance criterion. At the same time, depending on the soil type and the GD parameter being determined, the methods are divided into acceptable, unacceptable and conditionally acceptable (taking into account the limitation on the GD area).

4. Considering that a full calculation of all normalized parameters using the equivalence method can be performed only for soil type A, it is most advisable to use software packages that allow taking into account the three-layer structure of the soil in the process of determining the normalized GD parameters.

APPENDIX 1

An example of applying the proposed algorithm for selecting the equivalence method. The initial object has a size of 120×65 m^2 with depth of the soil location of 0,6 m. Soil parameters: ρ_1 = 53,9 Ω·m; ρ_2 = 117 Ω·m; ρ_3 = 12,3 Ω·m;

h_1 = 1,2 m; h_2 = 12,3 m. Accordingly, the soil is located in the first layer.

The given soil parameters correspond to soil type K, and the area of the soil is 7800 m^2 and meets the condition S > 2000 m^2. Therefore, to determine the touch voltage in the center of the GD (U_{tc}), one should use the equivalence method No. 1 according to expressions (1) and (2), according to the results of which the parameters of the equivalent model will be: ρ_{1e} = 53,9 Ω·m; ρ_{2e} =32,18 Ω·m; h_{1e} = 1,2 m. To determine the touch voltage at the edge of the GD (U_{tk}) using the equivalence method No. 3: ρ_{1e} = 53,9 Ω·m; ρ_{2e} = 32,32 Ω·m; h_{1e} = 0,8 m. In case of need to determine the voltage on the GD and the GD resistance, one should use a three-layer soil model.

Conflict of interest. The authors declare no conflict of interest.

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