

Optimization of the Amount of Coke Filling Usage in Cathodic Protection Systems for an Anode Grounding Model in the form of a Hemisphere

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Abstract. In this work, we calculated the optimal amount according to "annualized costs" criteria on the basis of model representations for anodic grounding of the cathodic protection system in the form of a single hemisphere, which is located on the surface of the ground and contains coke backfilling. At the same time, calculations were made for a similar grounding, but without the use of coke filling, which allowed comparative analysis and calculation of their comparative economic efficiency, depending on the specific resistance of the soil. As a result of these calculations, we proposed a modernized anodic grounding with a normalized amount of coke filling that has increased safety in comparison with the traditional product, since it allows reducing risks, caused by generation of positive DC stray currents of cathodic protection system, to other underground metal constructions. This quality of the proposed anode grounding is especially important in urban areas and at the territories of large industrial facilities characterized by an increased density of underground metal structures.

1. Introduction

The current state of fuel and energy complex of the Russian Federation and public utilities as a whole is characterized by increased accident risk of underground metal communications (UMC) and high degree of its wearing out [1-10]. This leads to increased amount of capital expenses for its reconstruction and maintenance. In this case, as the practice shows, the hazard having the highest priority is external corrosion of UMC. Special complex of anti-corrosion measures is used to eliminate this dangers, including its' cathodic polarization, which is associated with significant capital and exploitation expenses, especially for large cities and industrial sites [11-18]. Besides this, we observe a clear intensification of works of electrochemical protection against corrosion under the impact of AC stray currents [19-23]. In that context it is obvious that improvement of efficiency of active anticorrosion protection of underground metal pipelines (UMP) drastically reduces expenses both for construction of cathodic protection setups, and its' further exploitation [24-32] and thus may be regarded as priority direction of this technology development. World experience has worked out rather efficient way of cutting the reduced costs for cathodic protection by usage of coke filling at anodic grounding construction. Generally in this case the positive effect is achieved both by means of anode service life extension, and reduction of expenses for electrical energy [33], which is necessary for



electrochemical protection system functioning. The additional factor working towards usage of coke filling especially at urban conditions at presence of high UMP and other metal construction stacking densities is the following: reduction of area which is dangerous due to the presence of stray currents in the vicinity of anodic grounding. This work is devoted to consideration of two latter issues connected with implementation of traditional model representations, used for description of anodic grounding.

2. Optimization of the amount of coke filling for an anode grounding model in the form of a hemisphere located at the soil surface

Here we consider the simplest variant of cathode protection of the underground pipeline (figure 1), which includes transformer for cathode protection 1, cable gaskets 2 and 3, anodic grounding 4 and the metal pipeline 5 being protected, which is isolated from the outside environment using dielectric coating 6, i.e. polyethylene one. At this all system elements excluding transmitter and a part of isolated cable gaskets are located in the soil 7, whereas dielectric coating has defects 8 such that pipeline metal within its' bounds directly contacts with its surrounding soil or soil electrolyte.

We shall assume that anode for grounding of cathode protection setup (figures 1 and 2) is a single metal electrode, for example, made of iron. It has a hemispherical shape of radius r_0 , which is located at the soil surface, which is shown in figure 2a. Metal specific resistance is ρ_M , and specific resistance of the soil is ρ_g .

As metal specific resistance is extremely low and is significantly less than specific resistance of the soil, we will consider hemisphere surface as being equipotential and equal to potential at the cable input. From the other side, we may not take into account anode metal resistance in our further calculations. So, when our model is located in the soil and is infinitely distant from the pipeline, spreading resistance of anodic grounding R_g will be defined according to the following expression [34]:

$$R_g = \frac{\rho_g}{2\pi r_0} \quad (1)$$

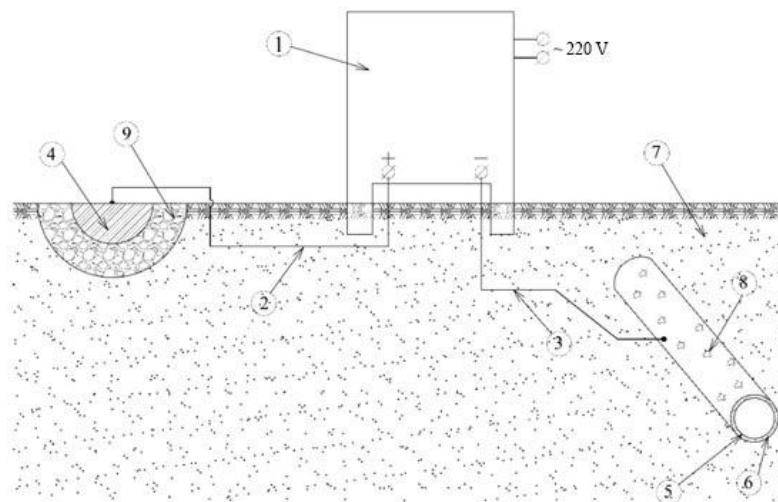


Figure 1. Cathodic protection scheme: 1 - cathodic station (transformer); 2,3 - cable gaskets; 4 - anodic grounding; 5 - metal pipeline being protected; 6 - polyethylene coating; 7 - soil; 8 - defect; 9 - coke filling.

When anodic grounding is at the same conditions, i.e. in coke filling (the soil is fully replaced by coke filling, figure 2b), its spreading resistance R_k will be defined by an analogue expression [34]:

$$R_k = \frac{\rho_k}{2\pi r_0} \quad (2)$$

where ρ_k is specific resistance of coke filling.

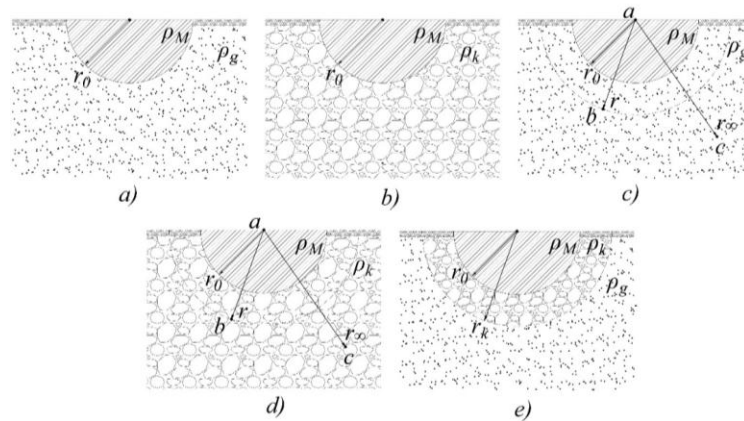


Figure. 2. Model of anodic grounding in a form of hemisphere, which is located at the ground (soil) surface.

We assume that r is a distance from anodic grounding center (point a) to a certain point (b) in soil or coke filling (figures 2c and 2d). In this case, taking into account symmetry of the object under test, resistance of soil layer from the end of radius-vector r (point b) to soil point (c) which is infinitely-distant from anodic grounding $R_{gr\infty}$ will be defined by the following equation (figures 2c):

$$R_{gr\infty} = \frac{\rho_g}{2\pi r} \quad (3)$$

Similarly, in case when the soil is totally replaced by coke filling (figures 2d), resistance of coke filling layer from the end of radius-vector r (point b) up to the soil point, which is infinitely-distant from anodic grounding (point c), might be calculated using the following mathematical expression:

$$R_{kr\infty} = \frac{\rho_k}{2\pi r} \quad (4)$$

From expressions (1) and (3) it follows that resistance of soil layer, which is located between anodic grounding and a hemisphere of radius r (figures 2c), will be defined by expression:

$$R_{gr_0r} = \frac{\rho_g}{2\pi} \left(\frac{1}{r_0} - \frac{1}{r} \right) \quad (5)$$

Similarly, expressions (2) and (4) show that in case when the soil is totally replaced by coke filling (figures 2d), resistance of coke filling layer which is located between anodic grounding and a hemisphere of radius r , might be calculated using the following mathematical expression:

$$R_{kr_0r} = \frac{\rho_k}{2\pi} \left(\frac{1}{r_0} - \frac{1}{r} \right) \quad (6)$$

By subtraction (6) from (5), we obtain the expression for calculation of change in anodic grounding resistance ΔR when replacing a soil layer by coke filling with radius, which is changing from r_0 to r_k (figure 2e). Consequently, the total soil resistance R_g , which is denoted by expression (1), will decrease by ΔR :

$$\Delta R = R_{gr_0r} - R_{kr_0r} \quad (7)$$

On substituting of the corresponding values into the right part of the latter expression, we obtain:

$$\Delta R = \frac{(\rho_g - \rho_k)}{2\pi} \left(\frac{1}{r_0} - \frac{1}{r_k} \right) \quad (8)$$

By using the latter expression together with the formula (1), we get the expression for calculation of the anodic grounding, which is located in a combined system: coke filling-soil. In this case coke filling is located in a hemisphere, limited by radius-vectors r_0 и r_k , whereas soil is located outside of

radius-vector r_k up to the infinity (figure 2e). Spreading resistance of the anodic grounding for the chosen shape and combination of coke filling and soil R_{kg} will be defined by the following formula:

$$R_{kg} = R_g - \Delta R \quad (9)$$

On substituting of the corresponding values into the right part of the latter expression, we obtain the following formula, which denotes spreading resistance of anodic grounding in the presence of coke filling:

$$R_{kg} = \frac{\rho_g}{2\pi r_k} + \frac{\rho_k}{2\pi} \left(\frac{1}{r_0} - \frac{1}{r_k} \right) \quad (10)$$

It is known [35], that cathodic protection current (I_0) is totally defined by characteristics of the protected construction and its environment. In this case, according to the cathodic protection scheme (figure 1) it is obvious, that at any change of anodic grounding characteristics, the value I_0 must stay constant. This fact allows us to determine power losses for anodic grounding at changing of its operating characteristics.

Annual expenditures for electrical energy C_g , which are associated with electrical resistance of anodic grounding which is located in the soil taking into account Joule-Lenz's law, are defined by the following expression:

$$C_g = KktI_0^2 R_g \quad (11)$$

where: K is a coefficient, which characterizes transformer efficiency (for example, at efficiency equal to 50%, this coefficient will be equal to 2); k is price for electrical energy (let it be equal to 4.00 rubles/kW·h); t is amount of hours in a year (8760); I_0 is total protective current passing through anodic grounding.

Similarly, expenditures for electrical energy C_k , which are associated with electrical resistance of anodic grounding located in coke filling, are defined by the following formula:

$$C_k = KktI_0^2 R_k \quad (12)$$

Combination of the latter three expressions results in formula, which defines electrical energy expenditures at anodic grounding, located in a combined soil;

$$C_{kg} = KktI_0^2 R_{kg} \quad (13)$$

In the meantime total economic effect of any measure in construction industry, is generally estimated using the term "annualized effect", which is defined by the following expression:

$$P = \frac{K_0}{T} + E_a \quad (14)$$

where: P is annualized cost in rubles; K_0 is capital expenditures for construction in rubles; T is object service life, years; E_a is annual exploitation expenditures in rubles.

It should be noted that usage of coke filling at construction of anodic grounding results in a number of positive effects, including reduction of power losses. For example, in this case [34] the anodes service time increases; electrochemical overload at anodic grounding reduces due to drastic growth of reactional surface; the necessary installed capacity of cathodic protection transformer reduces. Also it is quite likely that expenditures for maintenance service of cathodic protection setup slightly decrease. However, analysis of these issues go beyond the declared subject, so here we won't take them into consideration.

As it follows from formula (14), the total economic effect associated with economy of electrical energy at usage of coke filling, slightly decreases due to coke price and additional expenditures for its delivery and laying. In construction industry at rough estimations of work price it is believed that delivery and usage of material is equal to its price. We will use this wide-spread approach for estimation of works for coke laying at construction of anodic grounding. In this case for coke filling laying service, including material price K_k , we obtain the following expression:

$$K_k = k_a a D \frac{2\pi}{3} (r_k^3 - r_0^3) \quad (15)$$

where: k_a is a coefficient, which characterizes expenditures for delivery and laying of coke filling with respect to material cost (for example, at material cost equal to cost of its delivery and laying, this coefficient is equal to 2); a is price of coke filling unit weight, rubles/kg; D is coke filling density, kg/m³.

So, capital expenses for construction of anodic grounding K_0 , which enter the formula (14) are described by the following expression:

$$K_0 = K_a + K_k, \quad (16)$$

where: K_a is capital expenses, which include price, delivery and laying of the sacrificial anode, In our case these expenses are constant.

To calculate annualized expenses P according to formula (14), we should define annualized capital expenses K_0/T and annual exploitation expenses E_a . It should be noted, that according to (15) and (16) the value K_0 is an increasing function, which changes from a certain constant up to infinity. Its definition range is from r_0 to infinity. At the same time function C_{kg} with the same definition range is a decreasing function from a certain constant up to zero, which is seen from (13). As during analysis of exploitation costs of anodic grounding we take into account only expenses for electrical energy, we shall assume that $C_{kg} \approx E_a$. Consequently, on the basis of physical nature of K_0 and C_{kg} (both functions depend on radius-vector r) and taking into account that anodic grounding service life is equal to or more than zero, we may state that annualized costs P from (14) have a certain minimum value at r_k changing. In order to find this value we will use the fact that for continuous functions its derivative in bend point is equal to 0. By substituting the obtained values E_a и K_0 into (14), we get:

$$P = k_a a D \frac{2\pi}{3T} (r_k^3 - r_0^3) + \frac{K_a}{T} + K k t I_0^2 \left(\frac{\rho_g}{2\pi r_k} + \frac{\rho_k}{2\pi} \left(\frac{1}{r_0} - \frac{1}{r_k} \right) \right) \quad (17)$$

The latter expression we further differentiate with respect to r_k and equate to zero. After resolving it with respect to r_k we obtain the formula for calculation of optimum value of radius-vector r_{kr} :

$$r_{kr} = \sqrt[4]{\frac{(\rho_g - \rho_k) k K t I_0^2}{4\pi^2 a k_a D}} \quad (18)$$

where r_{kr} is value of vector r_k , which corresponds to optimum choice of parameters of coke filling from the viewpoint of expression (14).

Further we substitute the most common numerical values into this formula ($\rho_k = 0.2$ Ohm·m, $k = 4$ rubles/(kW·h), $K = 2$, $t = 8760$ h, $T = 10$ years, $I_0 = 1$ A, $a = 40$ rubles/kg, $k_a = 2$, $r_0 = 0.15$ m, $D = 800$ kg/m³, $K_a = 20\,000$ rubles). So we obtain the optimum "width" of coke filling as a function of specific resistance of the soil. Specific resistance of the soil we will vary from 10 Ohm·m (wet clay; sand, highly-watered by ground waters) up to 100 Ohm·m (semi-solid loam; moderately-watered sand). The calculation results are presented in table (Table 1) and graphical form (figure 3).

For comparison we will consider a variant of anodic grounding, where is no coke filling. Here for calculation annual exploitation expenses for anodic grounding without coke filling E_{ag} instead of (13) we use a modernized expression (11), which we denote as (11*):

$$E_{ag} \approx C_g = K k t I_0^2 R_g \quad (11^*)$$

For calculation capital expenses instead of formula (16) now we have to use the following expression:

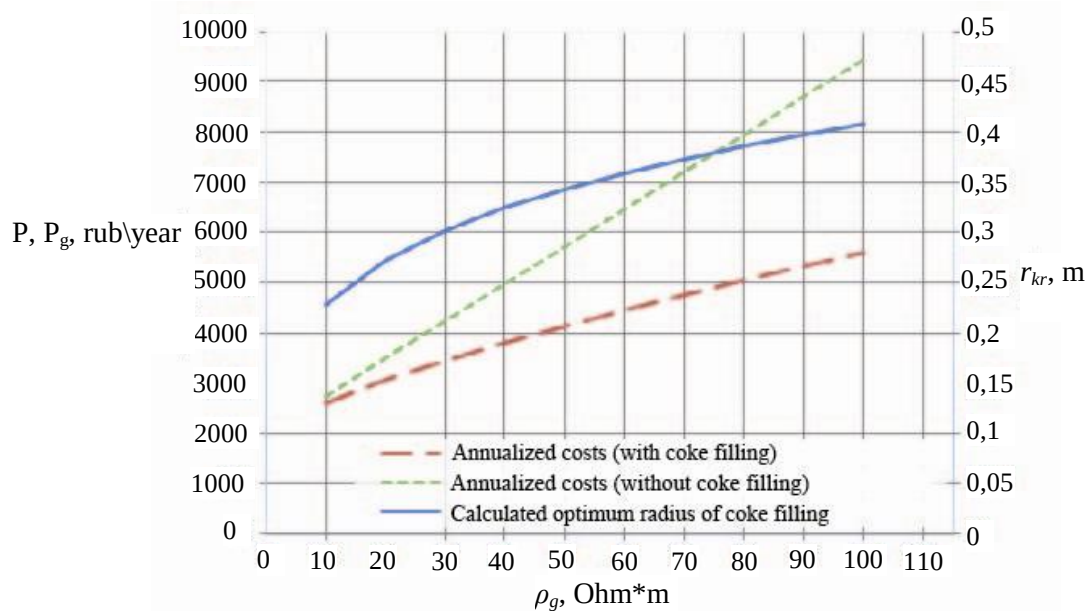
$$K_0 = K_a \quad (16^*)$$

Further we calculate annualized expenses for anodic grounding located at soil P_g using the modernized formula (19) and denoting it as (14):

$$P_g = \frac{K_0}{T} + E_{ag} \quad (19)$$

Table 1. Relation between major characteristics of a single hemispherical anodic grounding with optimum characteristics of coke filling and specific resistance of the soil ρ_g .

ρ_g , Ohm·m	$r_{kr}(r_r)$, m	R_{ka} , Ohm	K_a , rubles.	K_b , rubles	E_a , rubles.	P , rubles/year
10	0.228	7.04	20,000	1144	494	2608
20	0.272	11.79	20,000	2253	826	3052
30	0.302	15.95	20,000	3223	1117	3440
40	0.324	19.76	20,000	4114	1385	3796
50	0.343	23.34	20,000	4950	1636	4130
60	0.359	26.74	20,000	5745	1874	4448
70	0.373	30.00	20,000	6507	2103	4753
80	0.386	33.15	20,000	7242	2323	5047
90	0.397	36.20	20,000	7954	2537	5332
100	0.408	39.16	20,000	8647	2745	5609

**Figure 3.** Relation between annualized costs (P), calculated optimum radius of coke filling (r_{kr}), and specific resistance of the soil (ρ_g).

The calculation results are presented in table (Table 2) and graphical form for comparison with annualized costs in the presence of coke filling (figure 3).

Table 2. Relation between major characteristics of a single hemispherical anodic grounding without coke filling and specific resistance of the soil ρ_g

ρ_g , Ohm·m	K_a , rubles	E_{ag} , rubles/year	P_g , rubles/year
10	20,000	744	2744
20	20,000	1488	3488
30	20,000	2232	4232
40	20,000	2976	4976
50	20,000	3720	5720
60	20,000	4464	6464
70	20,000	5208	7208
80	20,000	5952	7952
90	20,000	6696	8696
100	20,000	7439	9439

Comparison of data from table and plots shows a significant decrease of annualized costs when using optimum parameters of coke filling during construction of anodic grounding, as well as strengthening of the positive effect at increase of specific resistance of the soil.

3. Impact of the amount of coke filling for an anode grounding model in the form of a hemisphere located at the soil surface on the area dangerous with regard to stray currents, going from anodic grounding

As before, r is a distance from anodic grounding center to a certain point in soil or coke filling (figure 2). In this case according to [34] anodic grounding potential φ_{gr_0} measured with respect to infinitely-distant ground will be defined by the following expression:

$$\varphi_{gr_0} = \frac{I_0 \rho_g}{2\pi r_0} \quad (20)$$

In the same time, soil potential φ_{gr} located at the distance r from the center of the anodic grounding might be described by the following expression [34]:

$$\varphi_{gr} = r_0 \frac{\varphi_{gr_0}}{r} \quad (21)$$

After substitution of numerical value of φ_{gr_0} from (20) we get the following:

$$\varphi_{gr} = \frac{I_0 \rho_g}{2\pi r} \quad (22)$$

According to the practice criterion [35] of estimation of danger with regard to stray currents going from the anodic grounding, the soil potential with respect to infinite-distant ground which is equal to +0.5 V and less is admitted to present no danger. Formula (22) allows us to calculate radius of the circle which is dangerous with regard to stray currents having its center in anodic grounding. After substituting into the formula (22) instead of φ_{gr} its numerical value (0.5V) and some transformations we obtain the following expression for calculation limits of dangerous area, which is formed by radius-vector r_{gro} :

$$r_{gro} = \frac{I_0 \rho_g}{\pi} \quad (23)$$

At usage of coke filling in a part of hemisphere, limited by radius-vectors r_0 и r_k , soil will be located outside of radius-vector r_k up to the infinity. So R_{kg} , which defines total resistance of the anodic grounding, might be calculated using the formula (10). Ohm law and formula (10) were used to calculate anodic grounding potential φ_{kgr_0} with respect to infinite-distant ground at the presence of coke filling. This was calculated for previously-chosen parameters, which characterize anodic grounding, soil and coke filling.

$$\varphi_{kgr_0} = I_0 \left[\frac{\rho_g}{2\pi r_k} + \frac{\rho_k}{2\pi} \left(\frac{1}{r_0} - \frac{1}{r_k} \right) \right] \quad (24)$$

In order to find soil potential φ_{kgr} located at the distance r from anodic grounding center in the case of presence of just coke filling, we rewrite the expression (20) in the following way:

$$\varphi_{kgr} = r_0 \frac{\varphi_{kgr_0}}{r} \quad (20^*)$$

By substituting the numerical value of anodic grounding potential φ_{kgr_0} from equation (24) to (20*), we obtain:

$$\varphi_{kgr} = \frac{r_0 I_0}{2r\pi} \left[\frac{\rho_g}{r_k} + \rho_k \left(\frac{1}{r_0} - \frac{1}{r_k} \right) \right] \quad (25)$$

Taking into account that according to danger criterion with regard to stray currents the potential φ_{kgr} should be equal to 0.5 V, secure radius r_B might be calculated from the latter formula:

$$r_B = \frac{r_0 I_0}{\pi} \left[\frac{\rho_g}{r_k} + \rho_k \left(\frac{1}{r_0} - \frac{1}{r_k} \right) \right] \quad (26)$$

However, in some cases more informative characteristics, which is necessary for analysis of this phenomenon is r_{BO} . It is a particular case of r_B value, which was calculated for optimum with regard to formula (18) value of coke filling radius. This approach allows us to modify formula (26) and to present it in the following way:

$$r_{BO} = \frac{r_0 I_0}{\pi} \left[\frac{\rho_g}{r_{kr}} + \rho_k \left(\frac{1}{r_0} - \frac{1}{r_{kr}} \right) \right] \quad (27)$$

Further we calculate numerical value of r_{BO} as a function of specific resistance of the soil using formula (27) and Table 1. This result we compare with anodic grounding without coke filling (23), which is characterized by radius-vector r_{gro} . In such case the reduction of danger area formed by radius-vector going from the center of a single anodic grounding Δr will be defined by the following formula:

$$\Delta r = r_{gro} - r_{BO} \quad (28)$$

However, in some cases more informative characteristics, which is necessary for analysis of this phenomenon is ΔS : gain in area which present no danger with regard to stray currents, which is connected with use of coke filling for anodic grounding. It might be calculated using the formula (29), obtained basing on the formula for calculation of circular ring area.

$$\Delta S = \pi \left(\frac{I_0 \rho_g}{\pi} \right)^2 - \pi \left(\frac{r_0 I_0}{\pi} \left[\frac{\rho_g}{r_{kr}} + \rho_k \left(\frac{1}{r_0} - \frac{1}{r_{kr}} \right) \right] \right)^2 \quad (29)$$

The calculation results are presented in table (Table 3) and graphical form (figure 4).

Table 3. Relation between characteristics of area , which is dangerous with regard to stray currents of a single hemispherical anodic grounding and specific resistance of the soil

ρ_g , Ohm·m	r_{kr} , m	r_{gro} , m	r_{BO} , m	Δr , m	ΔS , m ²
10	0.228	3.18	2.11	1.07	18
20	0.272	6.37	3.54	2.83	88
30	0.302	9.55	4.78	4.77	215
40	0.324	12.74	5.93	6.81	399
50	0.343	15.92	7.00	8.92	642
60	0.359	19.11	8.02	11.09	944
70	0.373	22.29	9.00	13.29	1306
80	0.386	25.48	9.94	15.53	1728
90	0.397	28.66	10.86	17.80	2209
100	0.408	31.85	11.75	20.10	2751

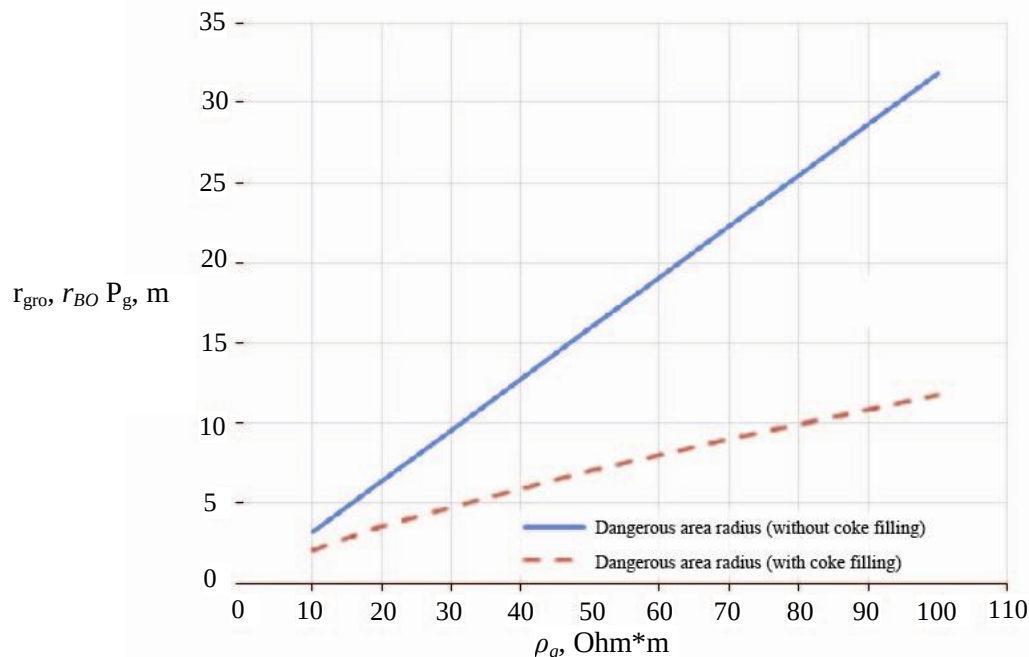


Figure 4. Relation between radius of the dangerous area in case of presence (r_{BO}) and absence (r_{gro}) of coke filling and specific resistance of the soil (ρ_g).

4. Results discussion and conclusions

In this work, we calculated the optimal amount according to "annualized costs" criteria on the basis of model representations for the anodic grounding of the cathodic protection system in the form of a single hemisphere, which is located on the surface of the ground and contains coke backfilling. Simultaneously we present calculations for similar grounding without coke backfilling. This allowed us to carry out comparative analysis and calculate its economical efficiency depending on specific resistance of the soil. As a result of these calculations, we proposed a modernized anodic grounding with a normalized amount of coke filling that has increased safety in comparison with the traditional product, since it allows reducing risks, caused by generation of positive DC stray currents of cathodic protection system, to other underground metal constructions. This quality of the proposed anode grounding is especially important in urban areas and at the territories of large industrial facilities characterized by an increased density of underground metal structures.

On the basis of our studies we can draw the following conclusions:

- We have proposed a technique for calculation of optimum amount of coke for hemispherical model of anodic grounding, which guarantees reduction of annualized costs. Also we present numerical estimation of this reduction at construction and further exploitation of anodic grounding for cathodic protection system for various values of specific resistance of the soil.
- We propose a technique for calculation the reduction of area which is dangerous with regard to positive stray currents at various values of specific resistance of the soil. It was used for hemispherical model of anodic grounding, which operates at optimum parameters from the point of view of annualized costs.

References

- [1] Bogdanov S, Sychov M, Lebedev L, Mjakin S and Gravit M 2016 Core-shell Powders for Additive Manufacturing of Articles for Underground Construction *Procedia Eng.* **165** 1579–86
- [2] Batkov E, Tarasova D, Andreev K and Limarenko I 2016 Technologies, Equipment and Construction Materials for Underground Infrastructure Development: Shear Forces in Bolts of Semi-rigid Joints for Steel Constructions *Procedia Eng.* **165** 1595–603

- [3] Svatovskaya L, Sychov M, Sychova A and Gravit M 2016 New Geocoprotective Properties of the Construction Materials for Underground Infrastructure Development **165** 1771–5
- [4] Kiselev V G 2015 Impact of ground electrical specific resistance on selection of cathode protection for underground pipelines *Sci. Tech. reports Peter Gt. St.petersbg. Polytech. Univ.* **3** 17–26
- [5] Romanovich M and Simankina T 2016 Urban Planning of Underground Space: The development of Approaches to the Formation of Underground Complexes - Metro Stations as Independent Real Estate Objects vol 165(Elsevier Ltd)pp 1587–94
- [6] Bobylev N and Sterling R 2016 Urban underground space: A growing imperative. Perspectives and current research in planning and design for underground space use. *Tunn. Undergr. Sp. Technol.* **55** 1–4
- [7] Dubitsky S, Greshnyakov G and Korovkin N 2016 Comparison of finite element analysis to IEC-60287 for predicting underground cable ampacity (Institute of Electrical and Electronics Engineers Inc.)
- [8] Ilin I, Kalinina O, Iliashenko O and Levina A 2016 Sustainable Urban Development as a Driver of Safety System Development of the Urban Underground vol 165(Elsevier Ltd)pp 1673–82
- [9] Utkina E, Pshennikov K and Braila N 2018 The Development of Underground Construction as a Way to Improve the Organization of Traffic **692** 356–66
- [10] Kudryavtseva T J and Kuporov J J 2015 Evaluation of social and economic efficiency of investments in public utility services *Asian Soc. Sci.* **11** 151–8
- [11] Suris M A and Lipovskikh V M 2003 *Protection of thermal networks of pipelines against external corrosion* (Moscow: Energoatomizdat)
- [12] Rodichev L V 2002 *Snizheniye resursa ekspluatatsionnoy bezopasnosti teplovykh setey i metody ikh zashchity* (Saint Petersburg: Izdatelstvo SPbGPU)
- [13] Rodichev L V 2006 *Effektivnost transporta teplovooy energii* (Saint Petersburg: Izdatelstvo OOO “Dom Shuan”)
- [14] Muradov A V., Ismaylova G G and Khasanov A A 2014 Some features of realization of joint electric protection *Neft. gaz i Bizn.* **4** 61–3
- [15] Muradov A V., Ismaylova G G and Khasanov A A 2012 Joint protection of two underground structures *Neft. gaz i Bizn.* **4** 44–6
- [16] Kodzhaspirov G E, Rudskoy A I and Rybin V V 2010 Effect of thermomechanical processing on structure and corrosion-mechanical properties of AISI 321 steel **89–91** 769–72
- [17] Kiselev V G, Sergeev V V and Rouzich E N 2017 Influence of the electric double-layer capacitance at the rate of corrosion at the phase interface *Corros. Rev.* **35** 47–51
- [18] Apostolopoulos C, Drakakaki A, Apostolopoulos A, Matikas T, Rudskoi A I and Kodzhaspirov G 2017 Characteristic defects-corrosion damage and mechanical behavior of dual phase rebar *Mater. Phys. Mech.* **30** 1–19
- [19] Baekmann W v. and Jakob R 1995 *Korrosionsschutz von Gas-und Wasserrohrleitungen* (Vulkan-Verlag Essen)
- [20] Bette U and Bornemann C 2008 Ergebnisse von Laboruntersuchungen zur Wechselstromkorrosion *3R Int.* **11** 641–5
- [21] Bette U 2016 Ergebnisse des Feldversuchens an einer durch Bahnwechselstrom beeinflussten Rohrleitung *3R Int.* **6** 40–5
- [22] Büchler M and Joos D 2016 Wechselstromkorrosion an kathodisch geschützten Rohrleitungen *3R Int.* **6** 46–52
- [23] Fischer M and Weber A 2016 Alternative Schutzstromversorgung in Verteilnetzen **6** 53–7
- [24] Kiselev V G and Kalyutik A A 2016 Influence of the cover layer of underground metallic construction on the efficiency of cathode protection *Izv. Vyss. uchebnykh Zaved. Probl. Energ.* **5–6** 27–36
- [25] Kiselev V G and Kalyutik A A 2015 The influence of soil resistivity in the area of

- underground pipeline on the efficiency of cathodic protection *Izv. Vyss. uchebnykh Zaved. Probl. Energ.* **1–12** 48–55
- [26] Kolbasnikov N G, Matveev M A and Mishnev P A 2016 Effect of structure factor on high-temperature ductility of pipe steels *Met. Sci. Heat Treat.* **58** 51–7
- [27] Muravyeva L V 2017 Simulation modeling in pipeline safety assessment (CRC Press/Balkema) pp 213–8
- [28] Strogonov K, Fedyukhin A, Stepanova T and Derevianko O 2018 Estimation of Practical Significance for Application of Composite Pipes in Comparison with Metal and Polymer Materials *Adv. Intell. Syst. Comput.* **692** 1024–35
- [29] Muravyeva L and Vatin N 2016 Elaboration of the Method for Safety Assessment of Subsea Pipeline with Longitudinal Buckling *Adv. Civ. Eng.* **2016**
- [30] Mentyukov K Y, Bortsov A N, Shabalov I P and Mansyrev E I 2016 Study of the Properties of the Base Metal of Large-Diameter Pipes Under Alternating Loading *Metallurgist* 1–8
- [31] Kolbasnikov N G, Mishin V V, Shishov I A, Matveev M A and Korchagin A M 2016 Surface-crack formation in the manufacture of microalloyed steel pipe *Steel Transl.* **46** 665–70
- [32] Silva C C, De Assis J T, Philippov S and Farias J P 2016 Residual stress, microstructure and hardness of thin-walled low-carbon steel pipes welded manually *Mater. Res.* **19** 1215–25
- [33] Kiselev V G 2013 Basic principles of design of cathodic protection of underground metal structures *Nauchno-tekhnicheskiye Vedom. SPbGPU* **4–1 (183)** 93–9
- [34] Baeckmann W and Schwenk W 1980 *Handbuch des kathodischen Korrosionsschutzes* (Verlag, Chemie)
- [35] Bette U and Vesper W 2005 *Taschenbuch für den kathodischen Korrosionsschutz* (Vulkan-Verlag Essen)