Optimization of Wire Anode Distance from Pipe in Impressed Current Cathodic Protection System

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Abstract: Installing wire anode alongside of a pipe is a common arrangement for impressed current cathodic protection system in complex plant, localized protection and congested areas. The installation cost and difficulties arise by increasing distance of anode as well as uncontrolled closing anode could cause overprotection in the nearest side of the pipe to anode while other part may not in the protection range. Hence optimizing wire anode-pipe distance is a general approach in this technology. For the first time, analytical equation is extracted for the common boundary conditions with general parameters included soil resistivity, pipe diameter and maximum allowable potential difference of the pipe surface. Based on the generated equation by considering 0.35 V maximum potential variation on the pipe, which is a potential difference between protected side with -0.850 V vs. $Cu/CuSO_4$ (CSE) and overprotection limit -1.2 V vs. CSE, in low resistive environment, 20-30 cm distance anode-pipe could produce even potential distribution for common size of pipes. In the same situation but moderate and high soil resistivity, the minimum distance is higher than mentioned value and also common available space in pipe trench. In these cases the minimum distance should be checked based on the extracted equation and obtained graphs or the number of anodes should be increased for reaching to the acceptable asymmetry in potential gradient. Moreover reducing the potential gradient gap will increase the effect of pipe diameter beside soil resistivity. The results approve by mathematical simulation of the system for the selected situations. FEM analysis by considering Butler-Volmer boundary condition for the cathode shows the nonlinearity of the polarized potential and possible hidden under- and over-protection area in wire anode-pipe common arrangement.

Keywords: Cathodic Protection; Wire Anode; Pipe; FEM; Numerical Analysis

Introduction

In cathodic protection, as an industrial method of corrosion protection, different shape and arrangement of external anodes are utilize to reach sufficient and even protection current density at cathode surface, such as pipe. Two main arrangements of anodes or anode groundbeds are (a) remote earth that could be deep well or far shallow groundbeds and (b) close groundbeds that could be shallow or semi-deep groundbeds or in such an extreme case very close anodes. Both mentioned arrangement is widely used in impressed current cathodic protection systems while the first category, remote earth, is not common for sacrificial anodes normally. Each anode-protection surface arrangement could have some advantage or disadvantage from both technical and economical point of view. For example in a plant, wire anode for piping is more costly than deep well but more conservative from technical analysis [1], while distributed shallow anodes are in middle from both economically and technically point view .

Nowadays wire anodes alongside the piping are a common and conservative cathodic protection design in case of congested area and several process piping close to each other. Some designer may recommend wire anode as a double protection for week coatings that coating replacement is not economical or practical. Sacrificial wire anode as grounding is not in the scope of this text. In all these arrangement, wire anode is install alongside the pipe within its sand filling area. In the impressed current cathodic protection wire anode normally are Ti-MMO or conductive polymer material. In some cases a coke backfill may use to increasing the current output and anode life. The main advantage of the wire anode installation is the even current distribution on the pipe and lowest possibility in current leakage to the nearby structures; however, there is an uncertainty in potential distribution and resistance calculation of wire anode-pipe arrangement in main reference books. In the lack of clear straightforward calculation, utilizing other cases instead of the correct equations could lead to unrealistic and inaccurate results [2-5].

Anode-pipe distance is a main design parameter for all types of the arrangement. In deep groundbed the remoteness is important, while in shallow distributed anodes installation, the closest point and maximum anode-anode is a parameter that should be calculated. These parameters extracted from potential gradient equations. For wire anode-pipe system the distance between anode-cathode is quiet constant but is not calculated normally and comes from some recommendation practices. This distance is important because when remotest point of cathode to the anode, in this case other side of the pipe, reach to the protection level, the closest area shall not go above the overprotection limits. This problem could not be evaluated and measured directly in practice. Because the reference electrode just could see the mean potential not potential of each point on the pipe surface [6, 7].

In the wire anode-pipe arrangement, as a rule of thumb, if the distance is increased, the potential distribution become more even. It could happened with two or four asymmetry anode arrangement too. If this distances is increased the execution cost will increase. In some cases because of foreigner structure and accessible area, increasing the distance is not practical. In the all mentioned cases, optimization is minimum possible distance from technical analysis, which has reasonably lowest cost.

For optimization and analyzing the wire anode-pipe system, at least two steps are required; first developing the analytical equations and then numerical analysis or simulation of the system. The analytical equation extracted from Ohm and Kirchhoff's laws by considering the two-dimensional specific geometry. The result of this equation is compared with finite element method (FEM) result. More complicated situation that is not possible to analyze by direct analytical equation is simulate by FEM too. Potential difference of two sides of the pipe, closest and remotest point, and also absolute value of the polarization potential is studied here too.

Analytical Equation Analysis

One of the most recognized methods in calculation of the anode resistance and potential distribution of the close anode in the cathodic protection system is presented by Baeckmann [3] in 1997. Later, Lazzari in 2017 reports more details on primary and secondary current distribution [2]. The proposed arrangement or the wire anode-pipe is:

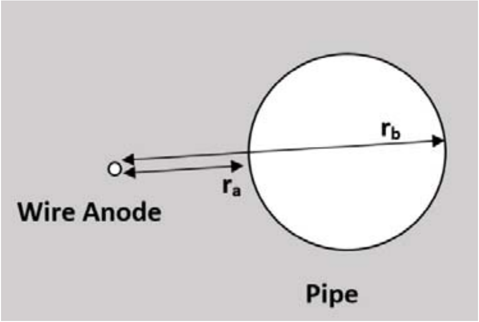

Figure 1: Schematic section of wire anode-pipe

Applying cathodic protection current as a stationary electric field, for electric field (E) and current density (J) and specific resistance (ρ) of the environment:

$$E = J\rho \tag{1}$$

While relation between electric field and potential (φ) at the "r" is:

$$E = -grad\ \varphi = -\frac{d\varphi}{dr} \tag{2}$$

So in polar coordinates:

$$\begin{aligned} \varphi(r) &= -\int E.dr \\ &= -\int J\rho.dr = -\int \frac{I.\rho}{S}.dr \end{aligned} \tag{3}$$

Baeckmann [3] explains that the field outside a local current lead is source free so surface integral is equal to a ground introduced current. With inputting boundary condition:

$$\ln\left(r_a + D_{pipe}\right) - \ln(r_a) = \frac{2\pi\Delta\varphi}{I\rho} \tag{4}$$

And:

$$\frac{D_{pipe}}{r_a} = \exp\left(\frac{2\pi\Delta\varphi}{I\rho}\right) - 1 \tag{5}$$

Real Data Analysis

For better evaluation and extracting some useful graphs, it is better to develop the equation 4 and 5 by some real data. If the minimum protection potential is assumed -0.85 V vs. CSE and the upper limit of the protection -1.2 V vs. CSE the allowable potential would be $\Delta\varphi$=0.35 V. For anode output 0.028 A, which is common for 3 mm diameter wire anodes in soil, the following graphs could extracted from the equation number 5:

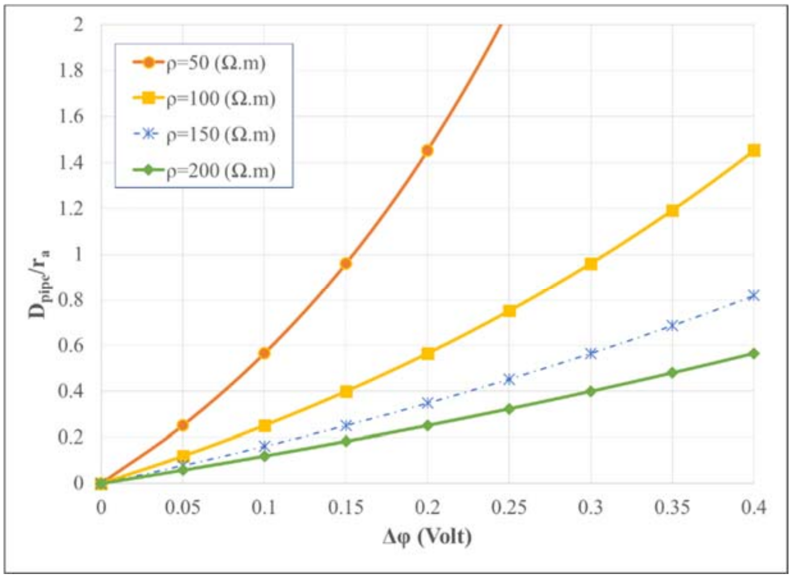

Figure 2: Pipe Diameter to Anode distance ratio vs. Potential difference on pipe surface in different soil resistivity

Numerical Solution (Finite Element Method –FEM)

Numerical solution by utilizing finite element method (FEM) use for evaluating the analytical equation and implementation of some complicated situation. Complicate situation here means, when conductive or non-conductive pipe cross the electric fields around the anode or in the more realistic case, cathode has a polarization behaviour with limiting oxygen reduction. Four different cases are:

CASE A: Cylindrical anode (Section of wire anode) at the centre. This situation is similar to the analytical equation assumption and although was used by reference books to generate straightforward equations [2, 3]

CASE B: A non-conductive circle (pipe section) cuts the electric fields line.

CASE C: A conductive circle (pipe section) is cathode.

CASE D: A polarizable circle (pipe section) is cathode. For the CASE D Butler-Volmer equation is cathode boundary condition that is graphically presentation is in Figure 3:

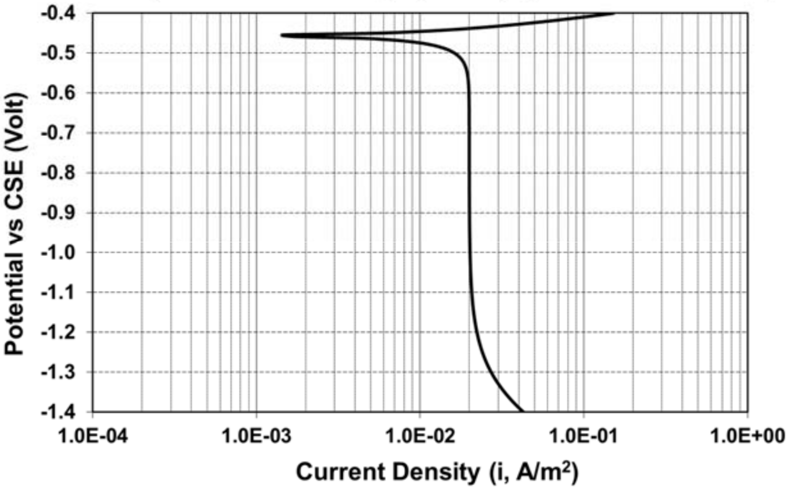

Figure 3: Graphical presentation of cathode boundary condition-CASE D

Current distribution and potential gradient are presented in Figure 4 and 5.

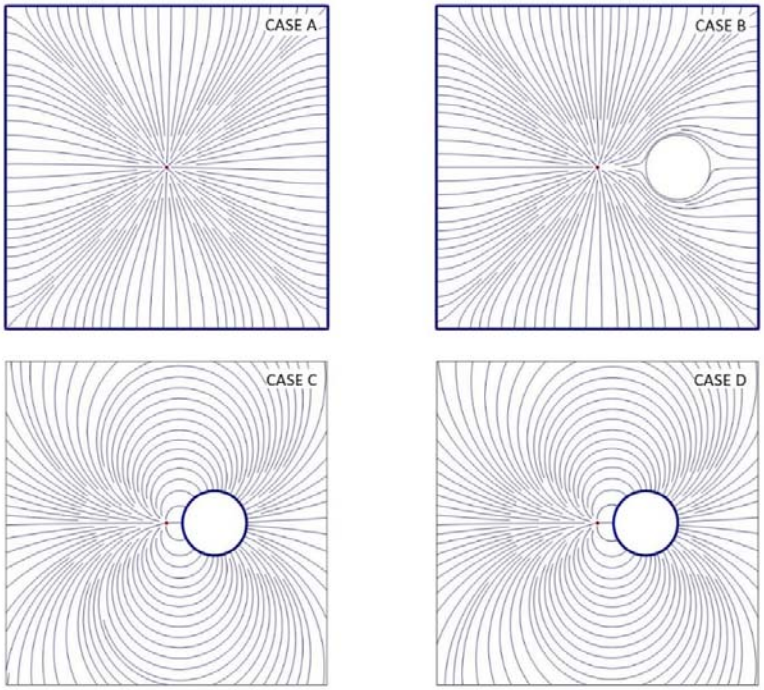

Figure 4: Current Distribution around the Anode and Cathode for Four Different Cases

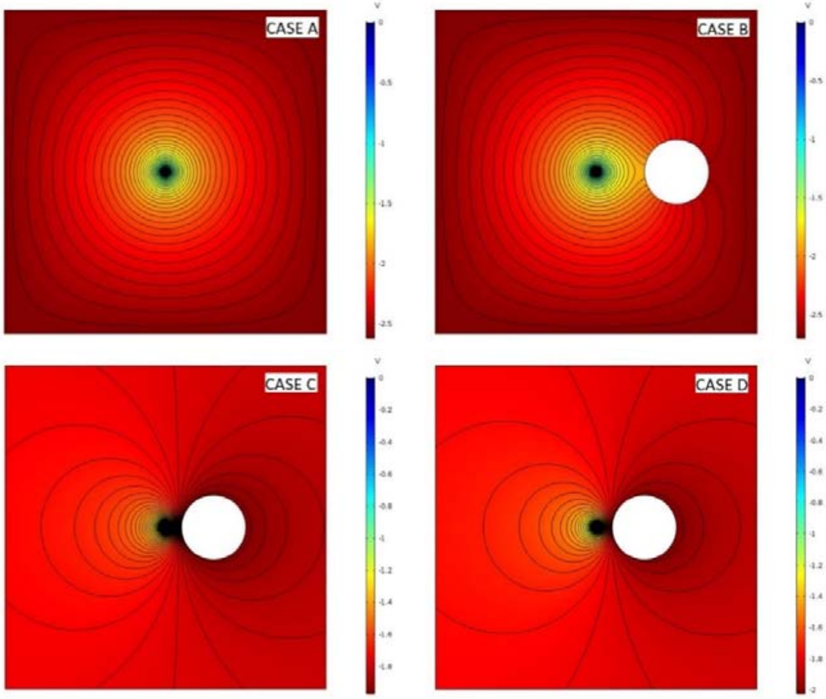

Figure 5: Current Distribution around the Anode and Cathode for Four Different Cases

Graphically, CASE C and D are similar but the numbers are little different. The potential difference between remote and close side is zero in CASE C but there is some potential difference in CASE D. The comparison between elaborated equations, equation 5, and CASE A are presented in Table 1, when $\Delta\varphi$ is the potential difference between near and far points of the pipe from the anode. For extraction of Table 1 data, in each case and condition, one simulation was run:

Table 1 : Comparison between potential difference from analytical equation and FEM simulation, CASE A (i=0.028 A.m^{-2} and ρ=100 Ω. m)

D_{pipe} (m)	**r_a (m)**	**$\Delta\varphi$ Equation 5 (V)**	**$\Delta\varphi$ CASE A (V)**
0.10 m (4 in)	0.10	0.309	0.307
	0.20	0.181	0.180
	1.00	0.042	0.043
0.25 m (10 in)	0.10	0.558	0.556
	0.20	0.361	0.361
	1.00	0.099	0.099
0.60 m (24 in)	0.10	0.867	0.863
	0.20	0.618	0.617
	1.00	0.209	0.210

In CASE D, which is the complete simulation model, secondary current distribution and polarization behaviour of the cathode are included too. This boundary condition is mentioned in Figure 3 and related description. For better understanding, protection current is utilized for extracting potential difference between close and remote points. In CASE D, as presented in Figure 6, the boundary conditions have highly effects on the results, so extraction of general equation for all the parameters is not possible or at least not useful.

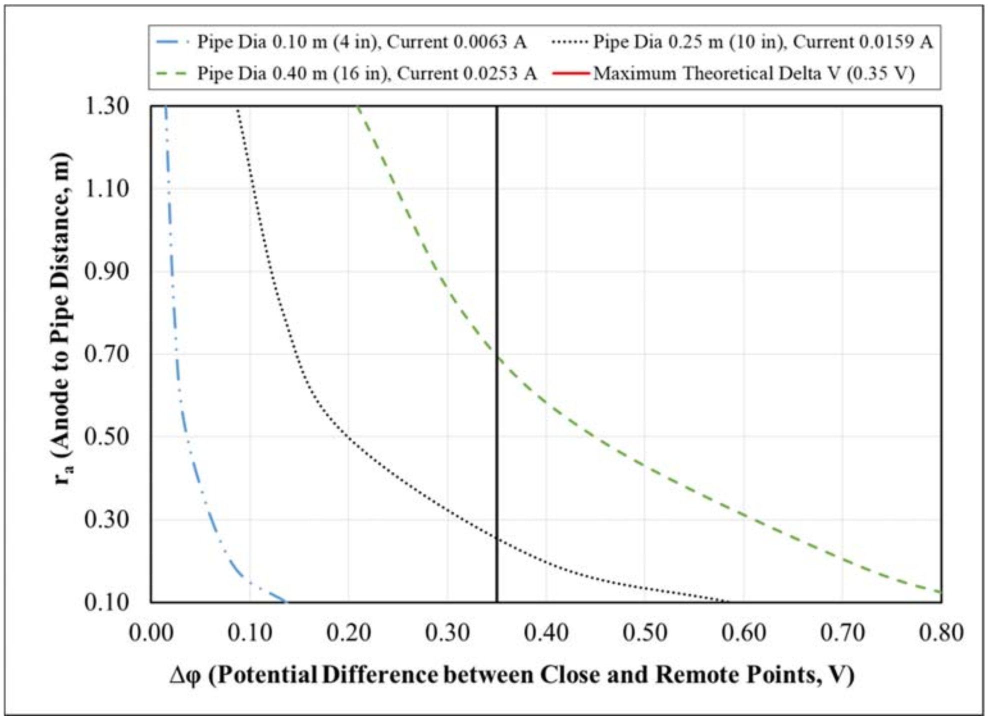

Figure 6: Potential difference between close and remote point (ρ=100 Ω. m)

Potential difference between two sides is one question that mentioned above, but another important question is absolute amount of polarization. FEM simulation solution of the CASE D for one pipe diameter is presented in Figure 7.

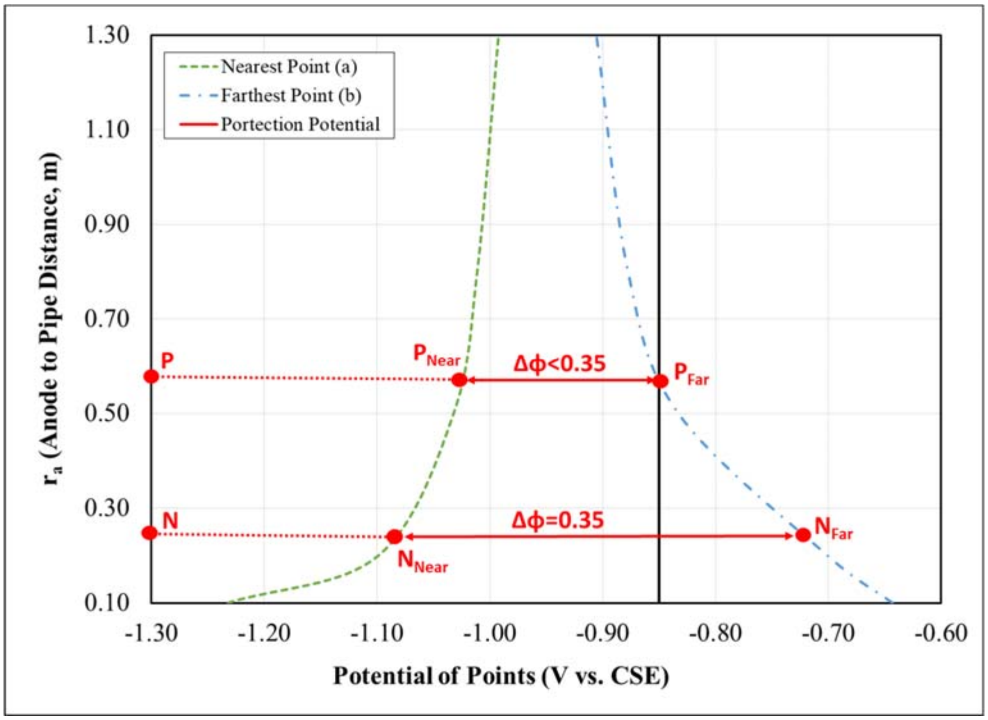

Figure 7: Polarization potential of two oposite point on a 0.25 m (10 in) diameter pipe (ρ=100 Ω. m and i=0.0159 A)

Discussion

In close groundbed analysis, it is common to consider just the shape of the anode. The main reason is that the cathode is in the potential gradient of the anode and cuts the equipotential lines, when the potential changes is considerable. These type of equations reported by Baeckamnn [3]. General equation 5 is reported for the first time here. The validity of the equation is approved by the numerical solution in the CASE A of this paper. The main and clearest result of this analysis is that the potential difference between closest and remotest to the anode is a function of the arrangement, soil resistivity and current output. So these parameters should be considered in the designing and optimizing of the wire anode-pipe distance in the CP systems and general recommendation such as fix distance between wire anode and pipe for all types of soils, pipe diameter or current output is not valid.

Figure 2, which is extracted from equation 5, shows that in the low resistivity environment with resistivity lower than 50 Ω.m, 20-30 cm distance between wire anode and pipe is reasonable. This soil resistivity range refer to the low resistive soil types or water saturated ones. In this rang, the closest and remotest point of the pipe to anode, in a common rang of pipe from 8 to 56 inches, do not suffer potential difference more than 0.35 volts. As it is clear in the Figure 2, in higher resistance soil and increasing the pipe diameter to distance ratio, the potential difference is much higher than expected and wire anode to pipe distance should be optimized. Based on the Figure 2, for a common dry clean soil with the resistance 100 Ω.m (yellow line), and for common range of potential difference (0.3-0.35 V), the graph shows the ration D_{pipe}/r_a close to 1 to 1.2. It means for pipe with diameter 0.6 m (24 inch), at least 60-70 cm distance is required and so for higher diameter, higher distance. When this distance is increased, the execution cost is increased and more excavation and preparing front work is necessary. In these circumstances, the optimization is not just considering one wire anode, maybe installation two or more anode for producing even potential distribution on the pipe surface could be an option. The numerical solution for CASE B is show us that the potential gradient changes in the case of none entering current to pipe is high. It has two meaning, first in the present of the foreigner non-conductive objects the potential gradient will be changes very rapidly and the second understanding is that in the high resistance coating, high potential tension on the coating could be expected. Comparison between CASE B and the case of ideal conductive cathode, CASE C, shows presence of defect in the high resistive coating will cause high potential gradient and should be evaluated carefully in the wire anode-pipe system.

CASE D, that has polarization behaviour of the cathode in its model, shows polarization is inevitable even in the high conductive body of the pipe. Hence, if the polarization behaviour eliminate, the potential difference of two side would not be realistic. The modelling of ideal potential gradient around the anode, CASE A, to non-conductive (CASE B), conductive (CASE C) and conductive polarizable cathode surface, CASE D, clearly show us the importance of the considering the boundary conditions and assumptions in the optimization of the wire anode-pipe distance.

Figure 6, which is FEM analysis of potential difference for different pipe size and protection current density, shows similar behaviour, as it is expected. Increasing the distance will reduce potential difference. Moreover, general scheme is same but changing the pipe diameter and current do not just shift the graphs, but also the slope and the curvature will change too. The boundary of 0.35 V potential difference is drawn as a solid black vertical line. This line shows even in common small pipe size such as 0.4 m diameter pipe, wire anode-pipe distance should be evaluated. This evaluation needs precise boundary condition definition.

Based on the empirical cathodic protection criteria, polarized potential is main criteria. One of the most applicable and recognized protection criteria for pipeline is polarized potential equal or more negative than -0.85 V vs. CSE. If this criteria apply for absolute polarized potential of the pipe surface, the FEM analysis of wire anode-pipe system with realistic boundary condition uncover a hidden error. From common potential measurement, the mean potential is measured. The 0.35 V gap analysis is necessary but it is not sufficient. In point N of Figure 7, the mean potential and 0.35 potential conditions are meet, but some part of the pipe is not in the protection. Therefore, in this circumstance the wire anode-pipe distance should be increased to the P point, around 0.6 m in this case, of the Figure 7. It means by utilizing FEM model and realistic boundary conditions, hidden polarization error could be found and the optimum wire anode-pipe distance is extractable.

Conclusion

The study based on both analytical and numerical analysis of the wire anode-pipe system show us:

- The wire anode-pipe distance is a function of the geometry, soil resistivity and current.
- For low resistivity soil, lower than 50 Ω.m, the wire-pipe distance could be in the range of 20-30 cm.
- For higher soil resistivity and pipe diameter, more distance is required and it should be carefully evaluated.
- For better understanding, numerical simulation is a useful tool, but the boundary condition should be defined precisely

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Symbols and Abbreviations

Term	Unit	Description
D_{pipe}	m	Pipe diameter
E	$V.m^{-1}$	Electric field
I	A	Current
i_0	$A.m^{-2}$	Exchange current density
i_L	$A.m^{-2}$	Limiting diffusion current density
J	$A.m^{-2}$	Current density
S	m^2	Surface
r	m	Distance and length
ρ	Ω.m	Specific Resistance
φ	Volt	Potential
β	V/decade	Tafel slope