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Effect of Anode-to-Cathode Distance on Corrosion Rate and Cathodic Protection of Submerged Low Carbon Steel in Riverine and Marine Environments

Omar Akram Ahmed*, Muthana Mahmood Kassim, Nabaa Hussan Abdul Razaq, Mohammed Najy Mohammed

Iraqi Corrosion Center, Corporation for Research and Industrial Development, Iraq

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****Corresponding Author:***
Omer Akram Ahmed
omerakramyaseen@yahoo.com

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Abstract

Corrosion of submerged steel structures, such as port piers, poses a significant threat to infrastructure durability, especially in aggressive aquatic environments. This study investigates the influence of anode-to-cathode distance on the corrosion rate and cathodic protection performance of low carbon steel using zinc as a sacrificial anode. Experiments were conducted using a Potentiostat MLab 200 system in two simulated environments, representing the riverine Abu Flos Port and the marine Khor Al-Zubair Port at anode distances of 5, 10, 15, 20, and 25 cm. Key electrochemical parameters including corrosion potential (Ecorr), corrosion current density (Icorr), and corrosion rate were obtained using Tafel extrapolation. Results indicated that the shortest distance (5 cm) provided the most effective cathodic protection in both environments, with Ecorr values reaching (–904 mV) and (–1044 mV), respectively. Correspondingly, the corrosion rate was minimized, demonstrating a strong inverse relationship between protection efficiency and anode distance. The zinc anode alloy used was also confirmed to meet ASTM B-418 standards for sacrificial anodes. These findings highlight the importance of optimal anode placement in cathodic protection design and confirm that zinc is an effective anode material in both riverine and marine environments. The study also validates the rapid assessment capability of the linear polarization resistance (LPR) technique for evaluating corrosion protection performance in submerged steel structures.

1. Introduction

Corrosion is one of the main problems that must be taken into account for iron structures, especially submerged ones such as docks, where a recent study estimated that the annual costs related to direct corrosion in the United States exceed 276 billion dollars or 3.1% of GDP [1]. Corrosion has been classified in various ways into [2]: (i) Chemical corrosion and electrochemical corrosion, (ii) Corrosion due to high and low temperature, and (iii) Dry corrosion and wet corrosion. Indirect interaction between metal and corrosive substances leads to the occurrence of electrochemical reactions similar to the reactions that occur in an electrochemical cell as a result of contact between the surface of the metal and an aqueous solution. This reaction, known as wet corrosion, is the focus of this study.

The corrosion of submerged structures (port pile) in water is caused by the difference in oxygen concentration on the surface from the inside of the water, where areas submerged in water are considered anode for areas with a high concentration of oxygen, which is considered a cathode, and as a result, corrosion occurs in areas submerged anode. Various methods have been developed to prevent corrosion in water areas, and one of these methods is cathodic protection, which is divided into two types [3]: (i) Protection systems using Impressed Current, and (ii) Protection systems using Sacrificial Anodes. This method protects metal surfaces by supplying direct current by passing a direct current to the metal with a low potential and converting all the anode areas located on the metal surface into cathode areas. This system is effective only for systems immersed in water or in soil. This protection system has successfully mitigated corrosion in sea vessels, coastal structures, pipelines, underground tank installations, etc. The use of sacrificial electrodes has advantages including simpler and more stable maintenance costs [4].when choosing the type of anode, the distance between the structure and the anode must be taken into account in order not to cause excessive protection if the distance is less than necessary or the level of protection collapses as a result of the distance, where the researcher (Komalasari) pointed out that the best distance was (1cm) in a saline solution with a concentration of 25000ppm and a corrosion rate of 0.694mpy [5]. The aim of the research to find the best distance between the anode and the cathode in the case of cathodic protection using sacrificial anodes, achieve the protection potential and obtain the lowest corrosion rate of submerged iron structures.

2. Experimental Procedure

In this research, the corrosion rate of the anodes was measured, where the distances between the zinc (anode) and the iron structure (cathode) were 5, 10, 15, 20 and 25cm, respectively, and the tests were carried out in river and marine environments and were classified on the basis of Table (1) [7] and the corrosion rate of the anode was measured under standard conditions using the dynamic system (Potentiostat M Lab 200), which consists of the following parts [6]:

1. Working electrode (WE): a sample of the zinc anode required to measure its corrosion rate.

2. Reference electrode (RE): an electrode with a constant electrochemical potential and used to measure the Potential of the working electrode in the galvanic cell, the most important types:
   - The calomel Reference Electrode (SCE) that was used in the research
   - The silver/Silver Chloride (Ag/AgCl) that is used in the field, for example (ports)

3. Auxiliary electrode (Counter Electrode (CE)): an inert electrode of the type:
   - Carbon steel type (Low carbon steel) (cathode) where the dimensions of the sample (1cm × 1.5cm) used in the work.

Table (1): Classification of water based on the value of TDS.

Classification	Total dissolved solids (parts per million)
Fresh	<1000
Brackish	1000-10,000
Saline	10,000-100,000
Brine	>100,000

As a result of the relationship between the electrical voltage and the logarithm of the absolute value of the corrosion current density (A/cm^2) for each sample (zinc anode) with an area of (1 cm^2), The corrosion rate (C.R) was calculated for it according to equation (1) [8].

$$C.R = \frac{0.00327 * Icor * E.W}{\rho} \qquad \textbf{(1)}$$

Where: C.R the corrosion rate is measured in units of (mm /y), Icor: absolute value of corrosion current density (µA/cm^2), E.W: equivalent weight of the test form (g), and ρ: density (g/cm^3).

3. Results and Discussion

X-ray fluorescence was used to determine the chemical composition of the elements that make up the zinc alloys and the results of the examination were as shown in Table (2).

Table (2): Chemical composition of zinc anode.

Element	**Al**	**Cd**	**Fe**	**Pb**	**Cu**
Alloy (wt %)	0.0065	0.00034	0.011	0.0437	0.000104
Element	**So**	**Si**	**P**	**Ca**	**Zn**
Alloy (wt %)	0.574	1.018	1.104	0.433	Balance

Carbon steel type (Low carbon steel) represents the inert electrode (auxiliary electrode) which was used in the research and represents the port pile. The chemical composition of the elements that make up the samples that were examined was determined and the results were as shown in Table (3).

Table (3): Chemical composition of the low carbon steel.

Element	**Mn**	**C**	**S**	**Pb**	**Fe**
Alloy (wt %)	0.7	0.18	0.01	0.02	Balance

Figure (1) shows the anodic and cathodic polarization curves of a zinc anode in a medium representing the Abu Flus port. These curves illustrate the electrochemical behavior of the zinc anode, as well as their potentials and current densities. Polarization behavior is crucial to understanding the efficiency of cathodic protection systems. Studies have shown that the position of the anode relative to the cathode significantly affects the distribution of protection currents. Bhuyan et al. demonstrated that the distance between the anode and the steel reinforcement affects cathodic polarization, with closer proximity resulting in a more uniform current distribution and effective corrosion mitigation [9]. This highlights the importance of optimizing anode positioning to ensure comprehensive protection of submerged structures.

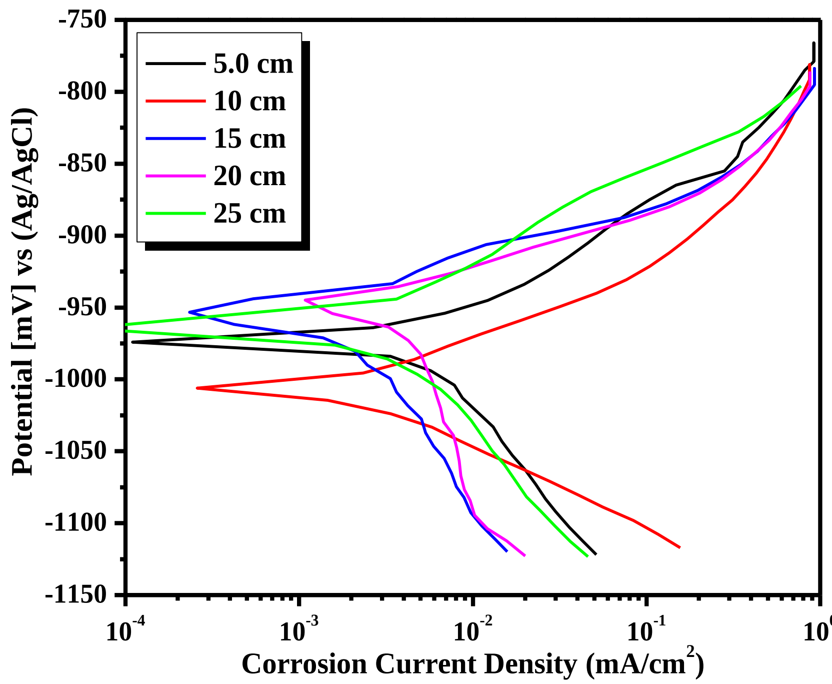

Figure (1): Polarization curves of zinc anode in simulated Abu Flos port environment.

Table (4) shows the experimental results obtained from the system in a medium simulating the Abu Flus port environment. The table includes measurements such as corrosion rate (mm/year), corrosion potential (Ecorr in mV), corrosion current density (Icorr in mA/cm²), open circuit potential (EOCP in mV), and the amount of dissolved salts in the medium in which corrosion occurred (TDS in parts per million) at different anode-cathode distances. The data reveal a trend in which the corrosion rate decreases with increasing anode-cathode distance. This observation is consistent with the results of previous research indicating that increasing the anode-cathode distance can lead to a decrease in protection efficiency due to poor current distribution [10]. Therefore, maintaining an optimal and minimum distance is essential for achieving effective cathodic protection.

Table (4): Electrochemical test results for zinc anode in simulated Abu Flos port environment.

Distance (cm)	TDS (ppm)	E_{OCP} (mV) Time = 0	E_{OCP} (mV) Time steady state = 15 s	Icorr (μA/cm^2)	Ecorr (mV)	Corrosion Rate (mm/y)
5	4884	-944	-960	2.27	-988.6	0.0338
10		-942	-945	2.09	-997.6	0.0311
15		-942	-948	1.38	-937.9	0.0205
20		-946	-957	1.04	-930.4	0.015
25		-940	-955	0.82080	-974.8	0.0122

Figure (2) illustrates the variation in corrosion rate with respect to the anode-cathode distance in the medium representing the Abu Flos port. The graphical representation shows a clear decrease in corrosion rate as the distance increases from 5 cm to 25 cm. This trend suggests that closer anode placement enhances the protective effect, likely due to more efficient current delivery to the cathode surface. Similar studies have reported that reducing the anode-cathode distance improves the uniformity and effectiveness of cathodic protection systems, thereby mitigating corrosion more effectively [11]. These findings emphasize the necessity of careful anode placement in the design of cathodic protection systems for submerged steel structures.

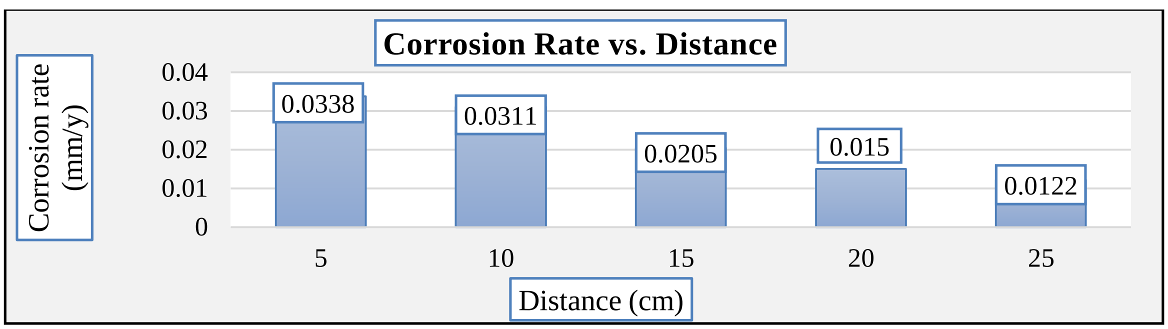

Figure (2): Variation of corrosion rate with anode distance in simulated Abu Flos port environment.

Figure (3) shows the anodic and cathodic polarization curves of a zinc anode in a medium representing Khor Al Zubair port. These curves illustrate the electrochemical behavior of the zinc anode, as well as its potential and current densities. Polarization behavior is crucial for understanding the efficiency of cathodic protection systems. Studies have shown that the position of the anode relative to the cathode significantly affects the distribution of protection currents. Chantal Chalhoub et al. demonstrated that the distance depends on the electrical resistance of the structure. It was found that when the cathode was connected to the anode, the rod closest to the cathode received the highest percentage of the total current, which increased with the electrical resistance, while the rods further away received very limited amounts of current [12].

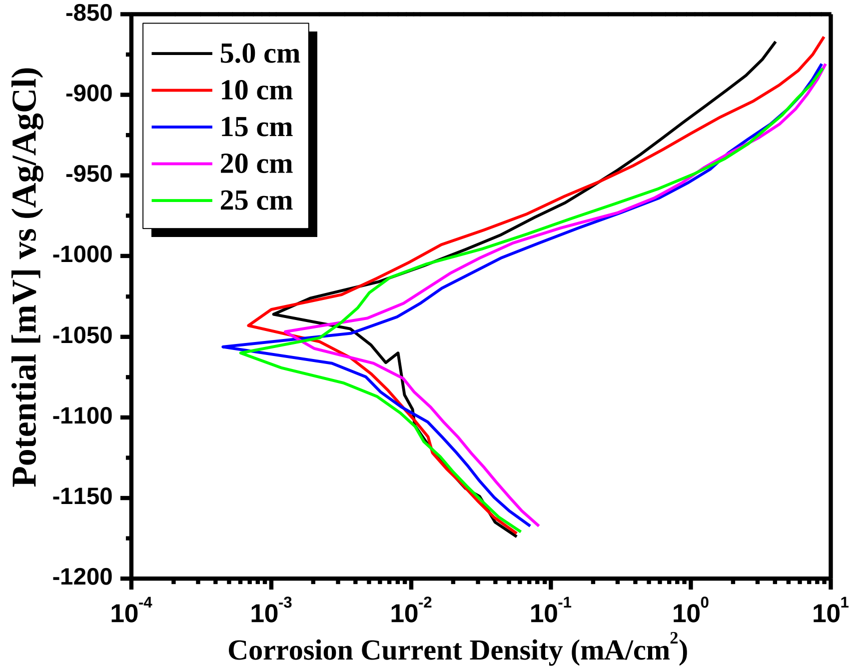

Figure (3): Polarization curves of the zinc anode in a medium representing the port of Khor Al-Zubair.

Table (5) shows the experimental results obtained from the system in a simulated environment of Khor Al Zubair Port. The table includes measurements such as corrosion rate (mm/year), corrosion potential (Ecorr in mV), corrosion current density (Icorr in mA/cm^2), open circuit potential (EOCP in mV), and the amount of dissolved salts in the medium in which corrosion occurred (TDS in parts per million) at different anode-cathode distances. The corrosion rate decreased with increasing anode-cathode distance. Adnan S. Jabr showed from the data he obtained that the cathodic protection current density increased with decreasing medium resistance and increasing anode-cathode distance. In addition, the cathodic protection current density for pipes coated with two different polymers increased with decreasing medium resistance and increasing the number of coating defects [13].

Table (5): Represents the results obtained from the system in a center representing the port of Khor Al-Zubair.

Distance (cm)	TDS (ppm)	E_{OCP}(mV) Time=0	E_{OCP}(mV) Time steady state = 15 s	Icorr (μA/cm^2)	Ecorr (mV)	Corrosion Rate (mm/y)
5	29000	-999	-1005	4.25	-1033.4	0.063665
10		-982	-1002	2.26	-1042.3	0.033854
15		-994	-1001	2.08	-1052.2	0.031158
20		-978	-996	1.7	-1046.3	0.025466
25		-987	-995	1.32	-1039.1	0.019773

The total dissolved solids (TDS) in Abu Flos water is approximately 4884 ppm, classifying it as brackish water, while the Khor Al-Zubair medium, with a TDS of 29,000 ppm, falls into the saline category. This difference in salinity directly impacts the conductivity and electrochemical aggressiveness of the environment. Saline water offers a higher ionic concentration, accelerating corrosion reactions and increasing the need for optimized cathodic protection strategies.

Figure (2) shows the corrosion rate in Abu Flos water decreasing from 0.0338 mm/year at 5 cm to 0.0122 mm/year at 25 cm anode-cathode distance. In comparison, Figure (4) displays a steeper initial corrosion rate in Khor Al-

Zubair water, declining from 0.0637 mm/year at 5 cm to 0.0198 mm/year at 25 cm. These observations indicate that the marine environment not only initiates more aggressive corrosion but also responds more significantly to changes in anode distance [14].

Figure (4) illustrates the variation in corrosion rates relative to the anode-cathode distance in the medium representing Khor Al Zubair Port. The graph shows a clear decrease in corrosion rates as the distance increases from 5 cm to 25 cm. This trend indicates that closer anode placement enhances the protective effect, likely due to increased current conduction efficiency to the cathode surface. These results emphasize the need for careful anode placement in the design of cathodic protection systems for submerged steel structures.

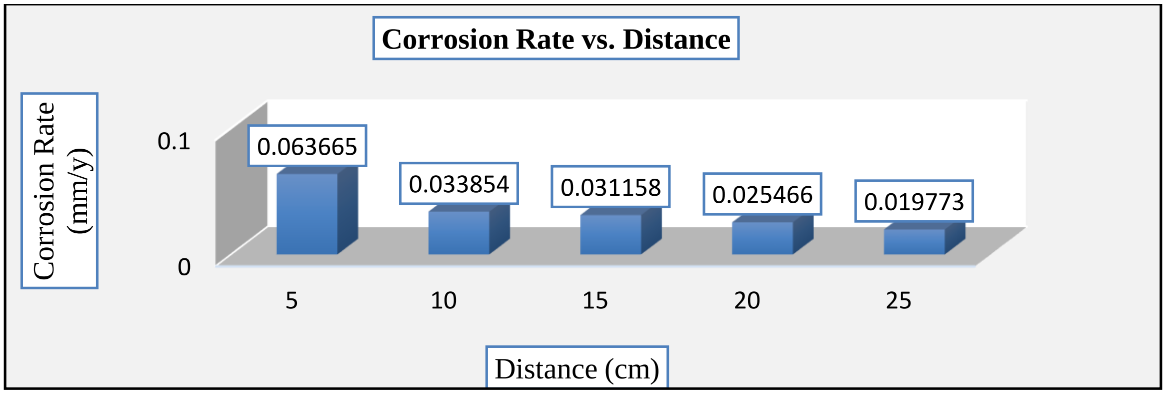

Figure (4): Corrosion rate change with distance in the center represents the port of Khor Al Zubair.

Figure (5) and Table (6) show the measurement of the cathodic protection potential of the ports of Abu Flus and Khor Al-Zubair after adding an anode (zinc) to a solution representing the environment of each of them. The readings were recorded, as the cathodic protection potential of the ports' substrates ranged from -900 mV to -1050 mV relative to the Ag/AgCl electrode, which is within the approved international standards [15].

Table (6): Cathodic protection potential for Abu Flos and Khor Al Zubair ports' piers after adding zinc anode.

Port Name	TDS(ppm)	Distance (cm)	$E_{closed\ Loop}$ (mV) Time steady state = 15 s
Port of Apoflos	4884	5	-900
		10	-906
		15	-904
		20	-900
		25	-906
Port of Khor Al - Zubair	29000	5	-1040
		10	-1044
		15	-1042
		20	-1040
		25	-1044

Figure (5): Comparison between the cathodic protection potential of the Abu Flos and Khor Al Zubair ports' foundations after adding the zinc anode.

4. Conclusions

The experimental results clearly demonstrate that the distance between the zinc sacrificial anode and the low carbon steel cathode significantly affects the corrosion rate and cathodic protection performance. In both simulated environments representing Abu Flos Port (riverine) and Khor Al-Zubair Port (marine), the shortest tested distance of 5 cm consistently provided the lowest corrosion rates and most favorable protection potentials. As the distance increased, the effectiveness of cathodic protection decreased due to reduced current density reaching the cathode surface. The cathodic protection potentials achieved at 5 cm (–904 mV in river water and –1044 mV in marine water) satisfy internationally accepted criteria, confirming the suitability of zinc as a sacrificial anode in both freshwater and saline conditions. In addition, the composition of the zinc alloy used aligns with ASTM B-418 Type II, ensuring long-term performance, especially in low-resistivity water. These findings emphasize the importance of optimizing anode placement in practical cathodic protection system design. Although the study was conducted under controlled laboratory conditions, the results offer valuable guidance for real-world applications. Future research should include long-term field studies and investigate the influence of water flow, temperature variations, and biofouling on protection efficiency.

Conflict of Interest: The authors declare that there are no conflicts of interest associated with this research project. We have no financial or personal relationships that could potentially bias our work or influence the interpretation of the results.

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