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Optimum Effect of Factors Influencing on Sacrificial Cathodic Protection for Steel Wall

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ABSTRACT

The Box-Behnken Design (BBD) is used to model the sacrificial Cathodic Protection System (SCPS) to find the factors effectiveness behaviour. For protection potential assessment the BBD receives (resistivity of environment, sacrificial anode alloy, distance between anode and cathode and surface area for the structure to be protected) as input and gives the protection potential as output. By applying BBD with their analysis tools we get many results. The important results which are the factors individual effectiveness on the sacrificial cathodic protection (SCP) process are the resistivity which has the greatest effect on the potential protection (rank=1) followed by sacrificial anode alloy type (rank=2), surface area for structure protected required (rank=3) and distance between anode and cathode (rank=4). The interaction of sacrificial anode alloy and cathode area ($\chi_2\chi_4$) has significant effect on CP process with the limits which are used in this work while the other factors interaction ($\chi_1\chi_2$, $\chi_1\chi_3$, $\chi_1\chi_4$,$\chi_2\chi_3$, $\chi_3\chi_4$) has insignificant effect on the limits which used in this work.

Keywords: Corrosion, Cathodic Protection, Sacrificial anode, Box-Behnken Design.

امثلية العوامل المؤثرة على الحماية الكاثودية بالتضحية لجدار الفولاذ

الخلاصة :

استخدمت طريقة الـ BBD لنمذجة نظام الحماية الكاثودية بالتضحية احصائيا لايجاد سلوك تاثير العوامل. لتقييم فولتية الحماية استقبلت الـ BBD (مقاومية الوسط، سبيكة الانود المضحي، المسافة بين الانود والكاثود، المساحة السطحية للبنية المحمية) كمدخلات واعطت فولتية الحماية كمخرجات. بتطبيق الـ BBDوادوات التحليل الخاصة بها . اهم النتائج للتاثير المنفرد للعوامل على عملية الحماية الكاثودية بالتضحية هي المقاومية التي امتلكت التاثير الاكبر على فولتية الحماية (المرتبة الاولى) يليها نوع سبيكة الانود المضحي (المرتبة الثانية), المساحة السطحية للانود المضحي (المرتبة الثالثة) والمسافة بين الانود والكاثود (المرتبة الرابعة). التاثير المشترك لسبيكة الانود المضحي ومساحة الكاثود ($\chi_2\chi_4$) امتلك تاثير قوي على عملية الحماية الكاثودية ضمن الحدود التي استخدمت في هذه الدراسه. بينما باقي التاثيرات المشتركة ($\chi_1\chi_2$, $\chi_1\chi_3$, $\chi_1\chi_4$,$\chi_2\chi_3$, $\chi_3\chi_4$) امتلكت تاثير ضعيف على عملية الحماية الكاثودية ضمن الحدود التي استخدمت في هذه الدراسة.

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INTRODUCTION

For carbon steel in seawater the normal corrosion potential E_{corr} is in the range -550 to -600 mV vs. Ag/AgCl [1]. The most effective method to overcome the corrosion is cathodic protection (CP) which represents a control method in the steel wall corrosion. Cathodic protection has been used in several areas including marine and underground structures, storage tanks, and pipelines [2]. Sacrificial anodes system generates protective current which depends upon the inherent potential difference between the anodes and the structure to be protected. If the structure is made of iron or steel, any metal that is more active in the electromotive force series can theoretically be used as anode material [3]. There are many factors influencing on cathodic protection like resistivity (NaCl content), chemical composition of sacrificial anode alloy, distance between anode and cathode, surface area of cathode, temperature, humidity, velocity of solution, dust, impurities, bacteria and etc. . The present work studied four factors: NaCl content, resistivity), chemical composition of sacrificial anode alloy, distance between anode and cathode, surface area of cathode) with different three levels of values for each one. Then this work will find the optimum value from the factors levels that tacked to investigated there influencing on sacrificial cathodic protection system.

Aim of This Work

The aim of research is to got the optimum effect of factors influencing on sacrificial cathodic protection for steel wall in seawater, and these factors which studied are resistivity, sacrificial anode alloy type, distance between anode and cathode and surface area for the structure to be protected.

EXPERIMENTAL EQUIPMENTS

Materials

Low carbon steel wall which is used in Al-Zubair Harper in the south of Iraq was used as a structure to be protected (cathode), three different anode alloys was used as sacrificial anode (Al-12%Si, Al-8%Zn, Pure-Al). The main cause to use this alloys type is related to the characterizes of the Al base alloys are use as sacrificial anode for cathodic protection in seawater environment because the light weight for the Al-base alloys. The proposed sacrificial cathodic protection, the handmade sacrificial cathodic protection system for conducting the experimental compaign is illustrated in ***Fig***. 1.

Experimental Setup

The experimental work includes the anode and cathode electrode preparation for the laboratory, sacrificial cathodic protection and potentiostate tests and include the solution preparation. The details of experimental setup are explained in [4].

Design of Experimental (DOE)

In any experimental campaign there is (K) number of independent variables and (ℓ) number of levels for each independent variable [5]. The number of experiments (S_n) for each type of EDM depends on the number of variables (K) and their levels (ℓ). It is worth noting that the Box-Behnken Design, besides other EDM types, is suitable for high numbers of variables of three levels [5] [6]. This is because the other EDM types result in higher number of experiments while BBD, reduce the required number of experiments to cover all the variables [5]. Assuming we have four factors (K=4) and three levels for each factor (ℓ =3), then the total number of required experiments using EDM traditional is calculated as follows [5] [7]:

$$\mathbf{S_n = \ell^k = 3^4 = 81 \text{ experiments}} \ ..... (1)$$

In fact, the classical or traditional DOE technique which is simple in planning and analysis, but it requires huge material and large time for conducting the experiments [10]. The BBD is one of the non traditional DOE techniques. All the non traditional DOE technique minimize the cost and time to do the experiments as they reduce the number of required experiments where each of them has own way to reduce the required number of experiment [10]. For example, for three levels, four factors only 27 experiments are required when using BBD EDM [5,8,9]. The BBD is nominated in this study.

Step of BBD Method

For achieving the desired potential protected for steel wall, the present investigation has been planned in the following steps:

1- Identifying the important factors, which influence the CP
2- Finding the upper, medium, and lower limits of the factors identified
3- Developing the experimental design matrix using BB design of experiments
4- Conducting the experiments as per the design matrix
5- Assessing the factors and their effects using response table and response graph
6- Assessing the real or chance effect of factors using normal probability plot
7- Optimizing the chosen factor levels to attain optimum effect on protection potential.

The details of parameters and their levels are summarized in Table (1) and the complete response table for three levels, 27 runs full factorial experimental design based on BBD is shown in Table (2).

EXPERIMENTAL WORK

During the experimental work, the cathode, anode, and reference electrode were mounted in their position. After the electrolyte (NaCl solution) preparation, the electrolyte was stirred by using mechanical stirrer to obtain a homogeneous solution and the temperature was fixed at room temperature (25-30 °C). When the bath reached the required set, the polarization electrical circuit was set to the (on) position in order to draw the curve of any given conditions (solution resistivity , type of sacrificial anodes, anode and cathode distance, and cathode area). After reaching to the stable reading of the specimen used, the run was stopped by removing the connection with the electrical circuit and finally emptying the water bath from the used electrolyte. The system was then washed by using tap water and distilled water to make sure that there was no electrolyte left in the system. This procedure was repeated exactly for other solutions and specimens. The cathodic protection measurements involve current and voltage measurements along the specimen for steel wall. The specimen, reference electrode, and sacrificial anode were fixed as shown in Figure (1). The electrode potential was measured with respect to saturated calomel electrode using multi-range voltmeter. Each experimental run took two hours at minimum up to stability and the potential versus SCE and current was recorded every four minutes.

RESULTS AND DISCUSSION

Main effects of factors and their levels on potential protected (OFAT)

Analysis of the below main effect plots indicates that a main effect occurs when the mean response changes across the levels of a factor see ***Fig***. 2. Therefore, it could can identify the strength of the effects of potential protected across factors by using the main effects plots as stated below.

- Resistivity: protected Potential ***increase*** when the resistivity moves from the high level to the low level of the resistivity.
- Sacrificial anode alloy: protected Potential **increases** when they move from the low level to the middle level then **decrease** when the move from the middle level to the high level of the sacrificial anode alloys type.
- Distance between anode and cathode: protected Potential ***increases*** when they move from the high level to the low level of the distance.
- Surface area for cathode: protected Potential ***increases*** when they move from the high level to the low level of the surface area for cathode.

The results refer to that the levels of factors r*esistivity (χ_1), distance (χ_3) and surface area for cathode (χ_4)* affect the response in a similar way. On the other hand, the levels of factor sacrificial anode alloy (χ_2) appear to affect the response differently. ***Fig***. 2 shows the large change in response effect estimated occurs with middle level (Zero-level) BBD is depending on Zero level in changing with response effects estimated.

Response graph

The effects of the four variables and their interaction are shown in Figure(3). According to the estimated effect graph, the sacrificial anode alloy type has the greatest effect on the potential protected followed by resistivity (rank=2), surface area for structure protected required (rank=3) and distance between anode and cathode (rank=4).

Normal probability plot

In response graph, it is found that some of the factor effects are larger than the other, but it is not clear, whether these results are real or chance. To identify the real effect, normal probability plot are used and is shown in Figure (4) which shows the normal probability of response potential and the all calculations for plot normal probability are summarized in Table (3) for potential protected response. Based on normal probability plots, the effects factors are close to the central middle line represent a chance effect (non-significant effect). On the contrary, effects of factors which are far away from the center line represent real effect or significant effect. As per the normal probability plot as shown in Figure(4), points (χ_2 χ_4, $\chi_2\chi_3$, $\chi_1\chi_3$, $\chi_1\chi_2$) which are close to a line fitted to the middle group of points represent estimated factors which do not demonstrate any significant effect on the response variable, on the other hand, the points (χ_1, χ_2, χ_3, , χ_4, $\chi_3\chi_4$, $\chi_1\chi_4$) appear to be far away from the straight line are likely to represent the real factor effects on the potential protected [10].

Interaction graphs

The interaction plots confirm the significance of interactions of factors. Interaction occurs when one factor does not produce the same effect on the response at different levels of another factor. Therefore, if the lines of two factors are parallel, there is no interaction. On the contrary, when the lines are far from being parallel, the two factors are interacting. This graph displays a full interactions plot matrix. Figure(5) represented the interaction effects of the factors on the potential response estimated. Interaction plot shown some pair factor interaction has significant effect and other pair factor interaction have insignificant effect on response effect estimated. Figure(5) explains the interaction of (resistivity and sacrificial anode alloy, resistivity and distance, resistivity and cathode, sacrificial anode alloy and distance, distance and cathode area) have insignificant effect on potential protected with the limits which inter in this work but if it was taken limit outer the study factors limits may will be significant because the tow line for factors will interact in far point as shown in Figure(5). While the interaction of sacrificial anode alloy and cathode area has significant effect on protected potential with the limits which used in this work because the tow factors line are interact as shown in ***Fig***.5.

CONCLUSIONS

1. The Box-Behnken Design is a systematic control tool to protect the steel wall against corrosion .The controller is flexible, and the curve mode corresponds well to the changing of the environment resistivity.
2. The factors individually effective on the CP process are the resistivity which has the greatest effect on the protection potential (rank=1) followed by sacrificial anode alloy types (rank=2), surface area for structure to be protected (rank=3) and distance between anode and cathode (rank=4).
3. The interaction of sacrificial anode alloy and surface cathode area ($\chi_2\chi_4$) has significant effect on CP process with the limits used in this work while the other factors in interaction ($\chi_1\chi_2$, $\chi_1\chi_3$, $\chi_1\chi_4$,$\chi_2\chi_3$, $\chi_3\chi_4$) have insignificant effect with the limits used in this work but if one takes the factors value out of the limit which is used in this work the effect of these interaction factors may be significant because the two lines for each pair of interaction factors will interact at distant point of the work limit.

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Table (1) Factors and their levels.

No.		Factor name	Upper level(+1)	Medium level(0)	Lower level (-1)
1	X1	Resistivity	3000	1500	25
2	X2	Sacrificial anode alloy	Pure-Al	Al-8%Zn	Al-12%Si
3	X3	Distance between anode and cathode (Cm)	30	20	10
4	X4	Surface area of structure protected required (Cm^2)	109	74	36

Table (2) The complete response table for three levels, 27 runs (protection potential).

No.	Potential (-mV)	X1			X2			X3			X4			X1 X2			X1X3		
		-1	0	1	-1	0	1	-1	0	1	-1	0	1	-1	0	1	-1	0	1
1	731	731			731				731			731				731		731	
2	766	766					766		766			766		766				766	
3	710			710	710				710			710		710				710	
4	688			688			688		688			688				688		688	
5	830		830			830		830			830				830			830	
6	792		792			792		792					792		792			792	
7	816		816			816				816	816				816			816	
8	783		783			783				783			783		783			783	
9	969	969				969			969		969				969			969	
10	961	961				961			961				961		961			961	
11	806			806		806			806		806				806			806	
12	753			753		753			753				753		753			753	
13	733		733		733			733				733			733			733	
14	746		746		746					746		746			746			746	
15	730		730				730	730				730			730			730	
16	737		737				737			737		737			737			737	
17	960	960				960		960				960			960				960
18	961	961				961				961		960			961		961		
19	774			774		774		774				774			774		774		
20	752			752		752				752		752			752				752
21	731		731		731				731		731				731			731	
22	747		747		747				747				747		747			747	
23	735		735				735		735		735				735			735	
24	746		746				746		746				746		746			746	
25	806		806			806			806			806			806			806	
26	806		806			806			806			806			806			806	
27	806		806		733	806			806			806			806			806	
Value	27	6	15	6	6	15	6	6	15	6	6	15	6	6	15	6	6	15	6
Avg.	791	891	770	747	733	838	734	803	784	799	815	780	797	738	803	710	868	779	856
Effect= high - low		144			105			19			35			93			89		

Table (2) The complete response table for three levels, 27 runs (protection potential).

X1X4			X2X3			X2X4			X3X4			X1X2X3			X1X3X4			X1X2X4			X2X3X4			
-1	0	1	-1	0	1	-1	0	1	-1	0	1	-1	0	1	-1	0	1	-1	0	1	-1	0	1	0
	731			731			731			731			731			731			731			731		731
	766			766			766			766			766			766			766			766		766
	710			710			710			710			710			710			710			710		710
	688			688			688			688			688			688			688			688		688
	830			830			830				830		830			830			830			830		830
	792			792			792		792				792			792			792			792		792
	816			816			816		816				816			816			816			816		816
	783			783			783				783		783			783			783			783		783
		969		969			969			969			969			969			969			969		969
961				961			961			961			961			961			961			961		961
806				806			806			806			806			806			806			806		806
		753		753			753			753			753			753			753			753		753
	733				733		733			733			733			733			733			733		733
	746		746				746			746			746			746			746			746		746
	730		730				730			730			730			730			730			730		730
	737				737		737			737			737			737			737			737		737
	960			960			960			960			960			960			960			960		960
	961			961			961			961			961			961			961			961		961
	774			774			774			774			774			774			774			774		774
	752			752			752			752			752			752			752			752		752
	731			731				731		731			731			731			731			731		731
	747			747		747				747			747			747			747			747		747
	735			735		735				735			735			735			735			735		735
	746			746				746		746			746			746			746			746		746
	806			806			806			806			806			806			806			806		806
	806			806			806			806			806			806			806			806		806
	806			806			806			806			806			806			806			806		806
6	15	6	6	15	6	6	15	6	6	15	6	0	27	0	0	27	0	0	27	0	0	27	0	27
884	778	861	738	801	735	741	801	739	804	789	807	#	792	#	#	792	#	#	792	#	#	792	#	792
106			66			62			18			**791.666**			**791.666**			**791.666**			**791.666**			**792**

Table (3) Normal probability calculations for protection potential.

Factor	Estimated Effects (Potential)	Rank Order (i)	Probability (Pi)=100(i-0.5)/10
χ_1	144	1	5
$\chi_1\chi_4$	106	2	15
χ_2	105	3	25
$\chi_1\chi_2$	93	4	35
$\chi_1\chi_3$	89	5	45
$\chi_2\chi_3$	66	6	55
$\chi_2\chi_4$	62	7	65
χ_4	35	8	75
χ_3	19	9	85
$\chi_3\chi_4$	18	10	95

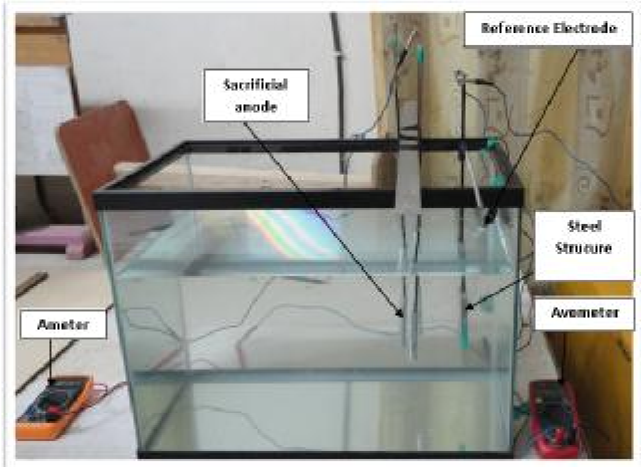

Figure.1 The Proposed Sacrificial Cathodic Protection System.

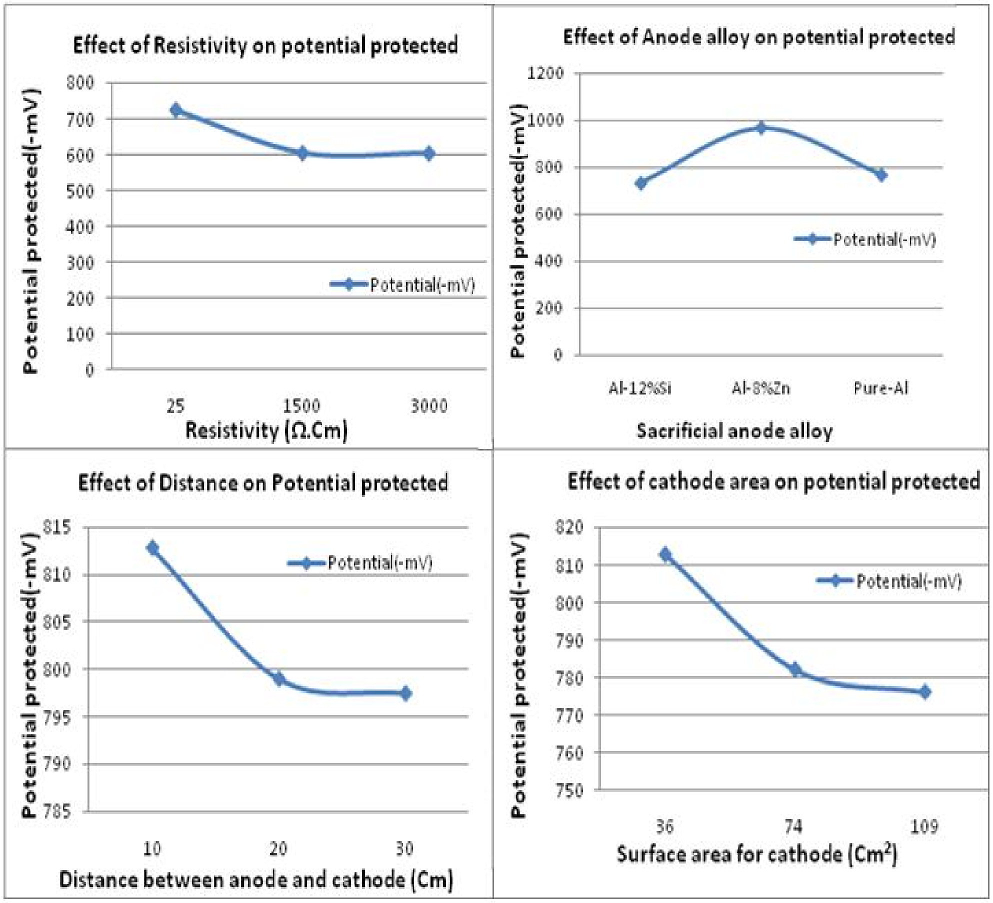

Figure. 2 Main Effects of Factors and Their Levels on Protection Potential for SCPS.

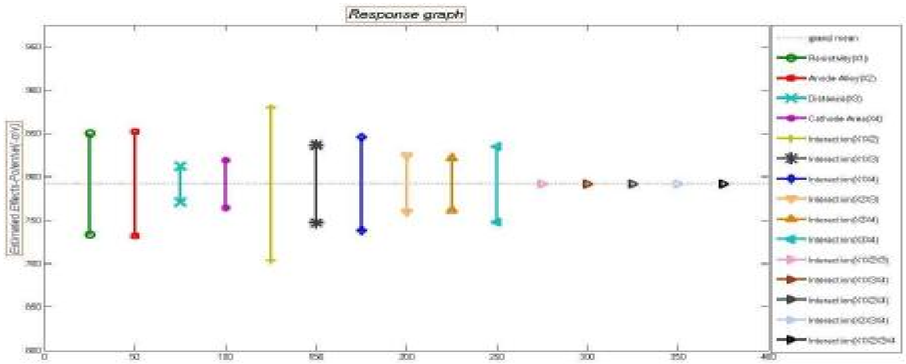

Figure 3 Response Graph of Estimated Effects-Potential (-Mv).

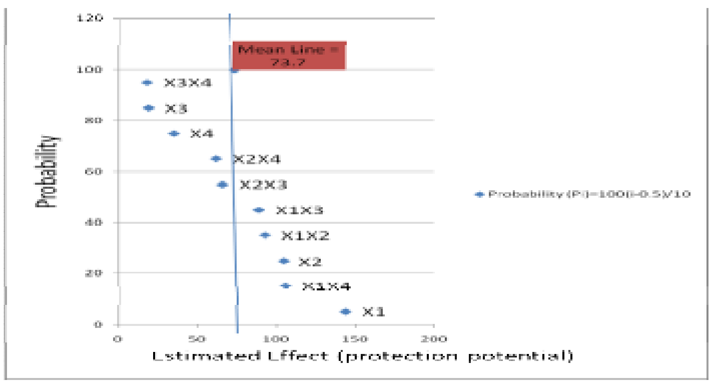

Figure 4 Normal Probability for Estimated Effects-Potential (-Mv).

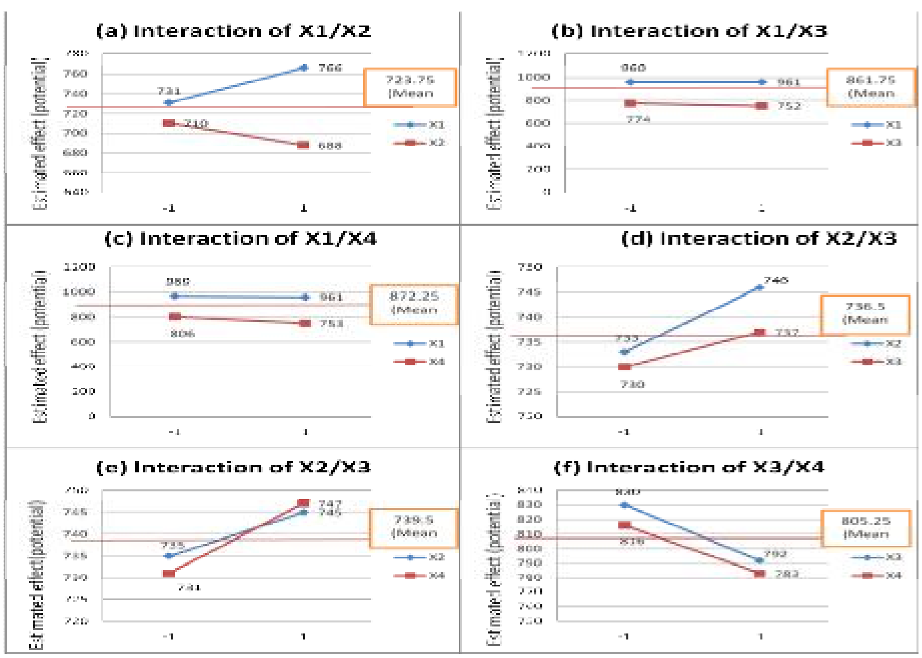

Figure. 5 Interaction Effects Plot for Pair Factors on Protection Potential.