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Statistical Approach to Underground Corrosion of Carbon Steel Pipeline

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Field corrosion studies were performed on polyethylene (PE) coated carbon steel gas transmission pipeline buried in Korea. Chemical and biochemical analysis of the soil adjacent to coating defects of pipes were performed at both field and laboratory. Correlation between the maximum corrosion depth and environmental factors was evaluated by applying statistical methods. The factors controlling corrosion were considered by linear regression analysis, principal component analysis (PCA) and multiple regression analysis. The corrosion site had a strongly positive correlation with chemical factors such as low pH and high levels of chloride, and anaerobic nature of soil that promoted the growth of sulfate-reducing bacteria (SRB), characterized by low level of soil resistivity and reduction-oxidation potential and finally on pipe-to-soil potential. It was proved that the statistical approach described results of field and laboratory works satisfactorily. Finally, the prediction equation for the maximum corrosion depth of carbon steel in soil environment is presented. It is important that the chemical, biochemical and cathodic protection (CP) effects should be considered together for the precise prediction of corrosion behavior in soil environments.

Keywords : *carbon steel pipeline, underground corrosion, sulfate-reducing bacteria, multiple regression analysis, maximum corrosion depth.*

1. Introduction

Underground metallic structures are always exposed to the danger of corrosion. Underground corrosion or soil corrosion may lead to disastrous consequences. For example, a leakage resulting from corrosion of underground gas pipelines usually causes fires or explosion, heavy economical losses and environmental hazards. A method of evaluating and predicting soil corrosivity correctly is needed so that necessary measures can be taken to prevent these tremendous accidents.

The process of underground corrosion is principally an electrochemical reaction similar to that in an aqueous solution. However, the corrosive phenomenon cannot be directly observed since the actual corrosion site is in the soil. Furthermore, it is thought that various kinds of chemical properties and microorganisms have an influence on the corrosion reactions[1] and these chemical and microbial factors usually interact in complicated way.[2] Therefore, the evaluation of soil corrosiveness has remained a troublesome problem.

Statistical approach is effective to identify areas of risk, i.e., correlating among the corrosive factors in an environment and the resultant corrosion and finally obtaining a regression equation for the prediction of corrosion risk.[3),4)]

It is well known that the rate at which corrosion pits grow in the soil under a given set of conditions tends to decrease with time and follows a power-law equation.[5]

$$P = kt^n \tag{1}$$

Where P is the maximum pit depth in time t, and k and n are constants.

If k and n can be determined using proper statistical methods, it becomes possible to predict the progress of corrosion in depth.

In this work, an attempt was made to investigate the effect of environmental factors on corrosion of underground polyethylene (PE) coated carbon steel pipeline. Field studies were carried out, and the relationship between maximum pit depth (P_{max}) and the measured environmental factors were analyzed statistically.

2. Experimental

2.1 Field survey

PE coated steel pipes (API 5L X65)[1] are used to

Table 1. Factors measured or investigated in the present field studies

No.	Factors	Unit	Symbol
1	Clay content	%	Clay
2	Burial depth	m	BD
3	Burial time	y	t
4	Existence of underground water	-	UW
5	Soil resistivity	$\Omega \cdot cm$	ρ
6	Water content	%	W_c
7	Sulfate ion (SO_4^{2-}) concentration	mg/g of soil	SO_4
8	Chloride ion (Cl^-) concentration	mg/g of soil	Cl
9	Alkalinity	mg/g of soil	Alk
10	pH	-	pH
11	Number of SRB	Cells/g of soil	SRB
12	Number of APB	Cells/g of soil	APB
13	Total organic carbon content	%	TOC
14	Reduction-oxidation potential	V/SHE	E_h
15	Pipe-to-Soil potential	V/CSE	P/S
16	Disbonded area of coating	cm^2	DA
17	Maximum pit depth	mm	P_{max}

construct natural gas transmission pipelines in Korea. During pipeline installation, pipe is welded at every 12 m and these girth weld joints are protected from soil environment by applying heat-shrink PE sleeves. The pipelines are also cathodically protected by impressed current system at the same time.[6]

A total of 16 environmental factors (Table 1) were measured where the coating defects were detected.

Soil resistivity (ρ), pipe-to-soil potential (P/S) were obtained by in-situ measurement in the field before excavation. Burial depth of pipes (BD), reduction-oxidation potential (E_h), the existence of underground water and maximum pit depth (P_{max}) were measured after excavation. Other factors were measured in the laboratory by examining sampled soils. The value of ρ was measured by ASTM G57 Wenner 4-point method.[7] E_h was measured as a potential of platinum (Pt) electrode using saturated copper/copper sulfate electrode (CSE) as a reference electrode and this value is presented vs standard hydrogen electrode (SHE) at pH 7. In final step of the field survey, pit depths were measured using depth gauge.

The content of anions was analyzed by ion chromatography. The population of SRB and APB was enumerated by most probable number (MPN) method.[8] Enumeration of microbes involves sequential inoculation of a triplicate series of dilution tubes containing Postgate's medium B[9] for SRB and fermentative anaerobic bacteria culture medium[10] for APB. Blackening of the tube after 21 days' incubation at 35 ℃ indicated growth of SRB. APB growth was revealed by a change in medium color from red to yellow. Standard probability tables were then used to estimate the density of viable microbes in the original sample.[8] Other soil parameters were analyzed by conventional soil analysis methods.[11]

2.2 Statistical analysis

After analysis of environment parameters, correlation between corrosion depth and each environmental factor was evaluated by statistical methods.

The distribution of data was investigated firstly by sample means, standard deviation, histograms and the like. Maximum corrosion ratio (the maximum depth of corrosion pit divided by the average value of the maximum depths of corrosion; P_0) was used as the criterion variable instead of P_{max}. Subsequently the relations among the variables and the existence of abnormal samples were investigated by the Pearson correlation coefficients (r) and scatter diagram. Parameter pairs having significant trends were selected based on a confidence level of 99%. After this, the variables were classified by the principal component analysis (PCA).

In order to predict the corrosion amount, a mathematical model expressing the relation between the quantity of corrosion and the reasons is required. As mentioned above, the equation (1) was adopted as the basic model.

$$P = kt^n \tag{1}$$

The predicting equation was obtained by multiple regression analysis. The model can be expressed by (2) by rewriting (1) using quantitative variable x_j's.

$$\log P_i = \alpha_0 + \sum_{j=1}^{q} \alpha_j x_j + \sum_{j=1}^{l} \sum_{k=1}^{q} \alpha_{jk} x_j x_k + \alpha_{q+1} \log t_i + \varepsilon_i \tag{2}$$

(i = 1, 2, ..., n: the number of samples)

wherein q : the number of variables
x_j : environmental variables
ε_i : error

This predicting equation considers the effects of single variables ($\alpha_j x_j$) and the interaction effects between variables ($\alpha_{jk} x_j x_k$) on the corrosion process.

In the multiple regression analysis, firstly coefficients α_j and α_{jk} of the environmental factors were determined by the least square method and then a coefficients α_{q+1}, of log t was its residual as the criterion variables.

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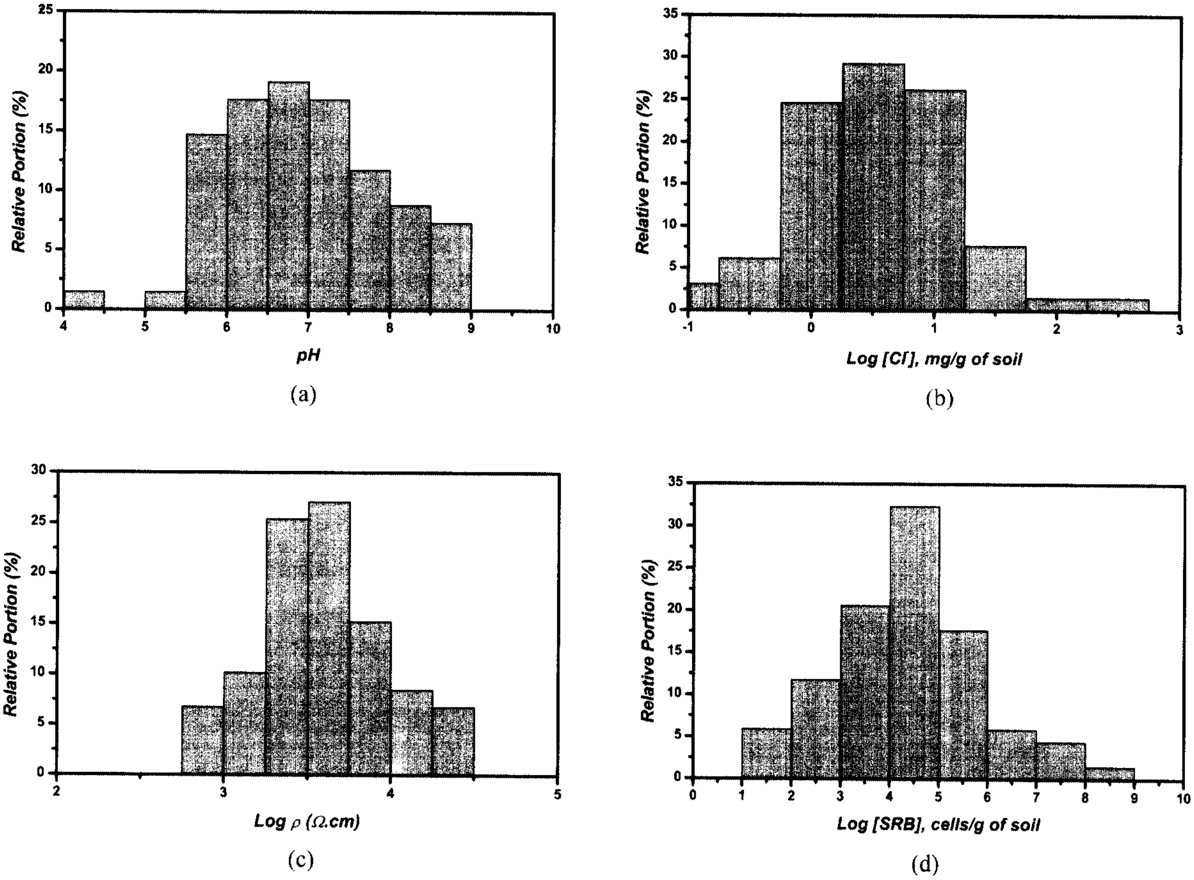

Fig. 1. Histograms of some environmental factors (a) soil pH, (b) chloride ion concentration, (c) soil resistivity, (d) the population of SRB

3. Results and discussion

3.1 Characteristics of soil samples

Measurements of the environmental factors showed the soil was characterized by:

- Broad spectrums for the values of environmental factors were found.
- Iron sulfides and UW were found at every site corrosion occurred.
- pH in the range of 4.2 to 8.5, which means the neutral soil environment.
- High levels of chloride at corrosion sites.
- High levels of SRB and APB at corrosion sites.
- The positive dependence of corrosion depth on P/S and DA was found.

Histograms of some factors are shown in Fig. 1.

3.2 Corrosion rates of PE coated carbon steel pipes

Fig. 2 shows the historgram of maximum corrosion depth obtained from the field studies. The maximum distribution was from 3 mm to 4 mm. Fig. 3 shows the typical corrosion morphology observed beneath disbonded shrink sleeve at weld of pipe. The characteristic of pitting corrosion was well developed. Every corrosion phenomena occurred in anaerobic soil characterized by low resistivity, E_h, high W_c etc. It was thought that SRB was introduced to corrosion processes. The details of investigative work are described previously.[6)]

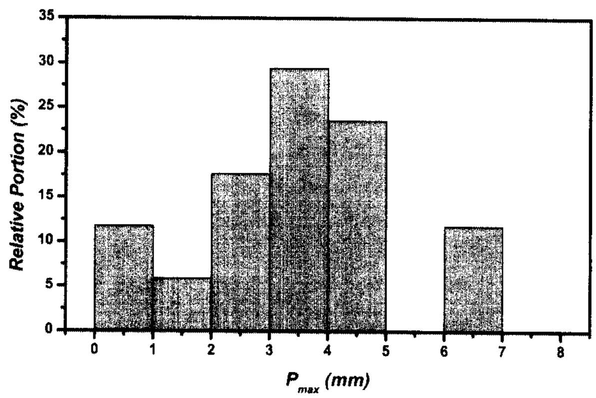

Fig. 2. Histogram of P_{max}.

Fig. 3. Corrosion found under the disbonded heat-shrink sleeve at weld of underground pipe

3.3 Correlation analysis

To investigate the correlation among the variables, Pearson correlation coefficient r was calculated. Table 2 shows results of the correlation analysis between P_0 and the environmental factors. Results for some factors are omitted because of poor correlation with P_0. The black circle reflected the effective correlation factors at the confidence level of 99%.

Close correlation was exhibited between the corrosion depth and the following variables: P/S, defect area (DA), SO_4, pH, SRB. r-values were 0.773, 0.682, 0.494, -0.502, 0.441, respectively. Fig. 4 shows the respective relationship between P_0 and P/S, DA, SO_4, pH, SRB.

It is also remarkable that the population of SRB is closely related with the population of APB, which comprise the MIC-related microbial community[1),12)] and with the anaerobic nature of soil, i.e., high organic matter level, low resistivity, high water content etc.

This favorable condition also promoted the corrosion process This means that the underground corrosion of carbon steel is affected by the activity of anaerobic microorganisms.

In addition, all corrosion phenomena occurred at the disbonded region of coating defects where the penetration of CP current was insufficient, and the P_0 increased as the disbonded area increased (Fig. 4 (b)). The dependence of P_0 on P/S and DA implicated that the corrosion process was strongly affected by the efficiency of CP. Therefore, the effect of chemical, biochemical factors and that of CP should be considered together.

3.4 Classification of environmental factors

It was found that there are correlations between P_0 and some variables. However, it would have been difficult to select outstanding factors correlating with severe corrosion because so many factors influence each other as shown in Table 2.

A second approach, PCA was undertaken to understand the nature of this complexity. The aims of PCA were to determine more precisely the interrelating with controlling factors affecting corrosion and to verify the validity of the previous discussion by predicting P_0 from the controlling factors. The factor loadings that are correlating coefficients between variables and principal components were plotted as shown in Fig. 5. It was judged from this

Table 2. Values of pearson correlation coefficient among environmental factors

	P_0^a	Alk^a	P/S	DA	SO_4^a	TOC	pH	SRB^a	Cl^a	APB^a	W_c	E_h	ρ^a	Clay
P_0^a		0.793	0.773	0.682	0.615	0.504	-0.502	0.441	0.408	0.386	0.358	-0.321	-0.292	-0.030
Alk^a			0.164	0.097	0.565	0.700	0.398	0.111	0.431	0.513	0.313	-0.156	-0.443	0.195
P/S	●			0.391	0.308	0.465	-0.392	0.289	0.375	0.479	0.339	-0.240	-0.290	0.112
DA	●				0.538	0.187	-0.486	0.511	0.566	0.404	0.249	-0.590	-0.384	0.095
SO_4^a	●	●		●		0.690	-0.046	0.467	0.484	0.467	0.250	-0.363	-0.375	0.079
TOC					●		0.304	0.110	0.279	0.268	0.161	-0.057	-0.247	0.242
pH	●	●	●	●				-0.156	0.079	-0.351	-0.046	0.068	-0.109	0.131
SRB^a	●			●					0.525	0.555	0.579	-0.580	-0.661	0.608
Cl^a		●	●	●	●			●		0.343	0.394	-0.366	-0.562	0.298
APB^a		●						●			0.419	-0.340	-0.342	0.386
W_c								●	●			-0.339	-0.637	0.278
E_h				●	●			●	●		●		0.638	-0.350
ρ^a		●						●	●			●		-0.416
clay								●				●		

a: log value.
●: pairs having effective correlation with the confidence level of 99%.

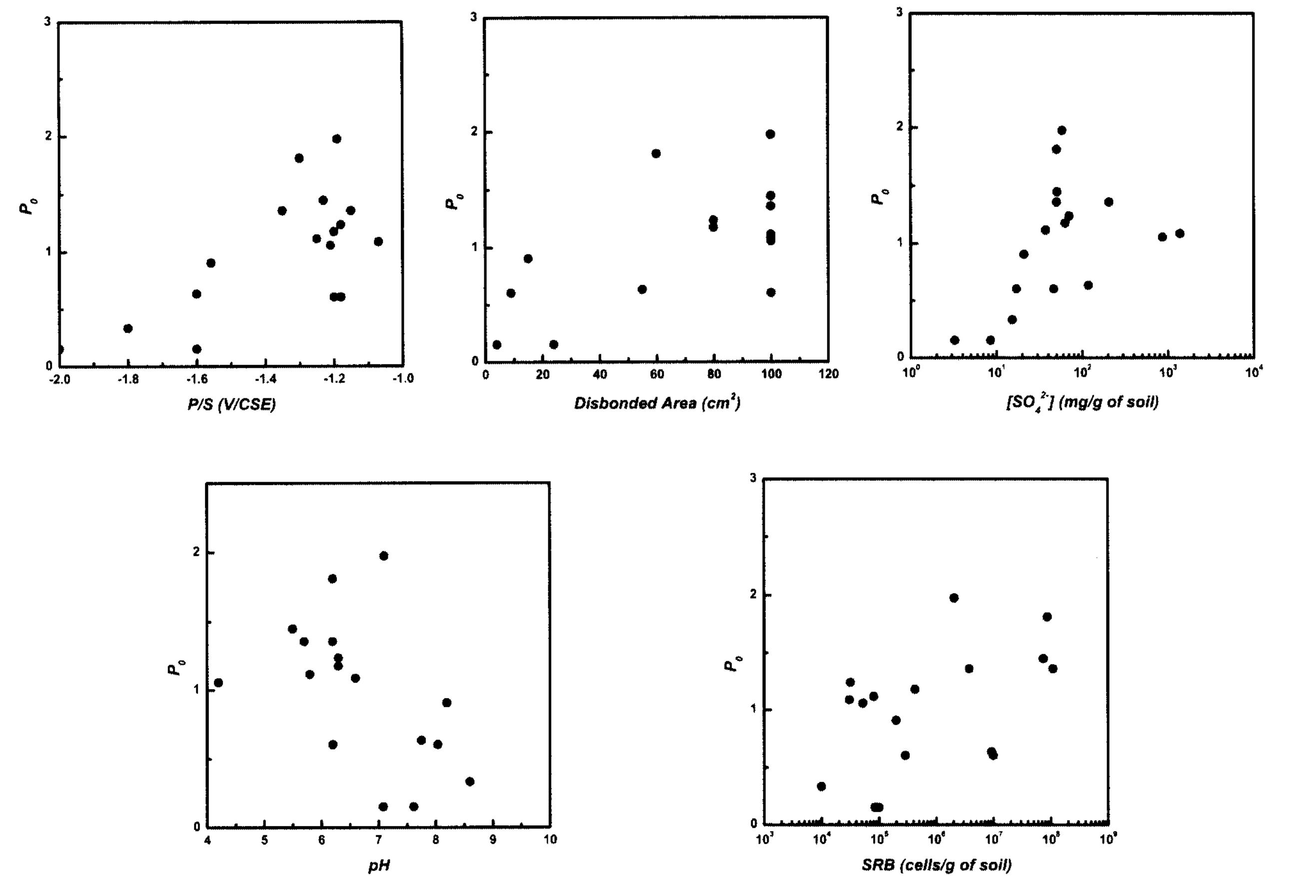

Fig. 4. Relationship between P_0 and environmental factors (a) P/S, (b) DA, (c) SO_4, (d) pH, (e) SRB

diagram that a group of variables encircled by a broken line belongs to one group having common characteristics.

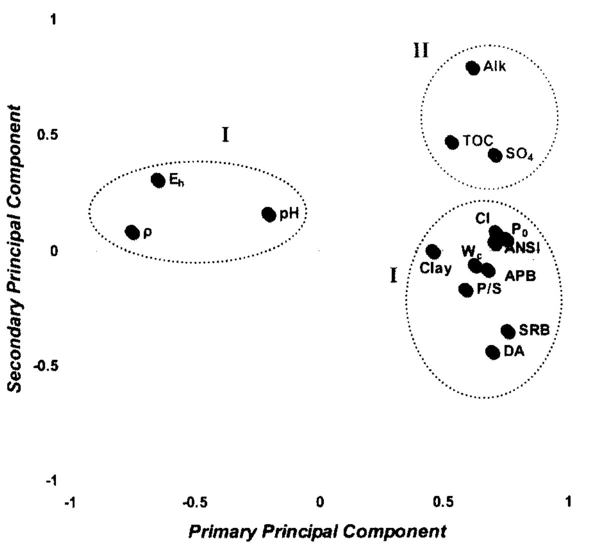

Fig. 5. Relation of Variables Obtained by PCA (plotted factor loading)

Two groups were found for this case and P_0 could be predicted by only considering "group I" and by ignoring "group II" with little error.

3.5 Analysis of the environment

The multiple regression analysis was conducted with corrosion ratio, P_0, as the criterion variables. The variables were selected by taking the results of the correlation analysis and PCA into consideration and adding judgment by proper techniques.

The multiple regression analysis was repeatedly run and the resultant regression equation comprising the following 6 variables in combination was judged to be most suitable in respect of practical use and statistical accuracy: 1) pH, 2) ρ, 3) Cl, 4) E_h, 5) P/S, 6) pH(ρ .

Arranging the above-mentioned results, the equation (3) is obtained with P_c as the predicted value of P_0.

$$LogP_c = 11.70 - 1.31pH - 3.08E_h - 0.56Log\rho + 0.16Log[Cl^-] + 0.78P/S + 0.37pH \cdot Log\rho \quad (3)$$

3.6 Prediction of corrosion rate

Thus, k in equation (1) was obtained by (3), i.e., the first and second terms on the right side in (2). In order to predict the corrosion rate, it is necessary to determine n in (1). Therefore, n was determined as the regression coefficient for the linear model of (4) with the residual of (3) as the criterion variable.

$$\log P_0 - \log P_c = A + n \log t \qquad \text{(A:constant)} \qquad (4)$$

From this regression process, P_0 can be predicted from the corrosiveness of the environment and the burial period by (5)

$$P_{0,cal} = 0.49 P_c t^{0.38} \qquad (5)$$

wherein, $P_{0,cal}$: the predicted value of P_0
P_c: the evaluation value of the environment in corrosiveness (according to (3))
t: the burial time (y)

The correlation coefficient between P_0 and P_{cal} was 0.917. Fig. 6. is the scatter diagram of P_0 and $P_{0,cal}$. Data fell closely on the straight line with the slope of 0.831. Therefore, the result of statistical analysis supported satisfactorily the validity of the previously mentioned understanding.

It was found from this result that three effect contributes to underground corrosion process; 1) chemical effect (pH, Cl and pH(ρ), 2) biochemical effect (E_h and ρ) which affects to the activity of anaerobic microorganism such as SRB, 3) the effect of cathodic protection (P/S). The corrosivity of soil is evaluated by analyzing the chemical and biochemical properties of soil itself. However, it is important that the corrosion did not always occurs at all defects of coated pipe steel even though the adjacent soil is corrosive, i.e., low ρ, low E_h, low pH, high level of chloride, etc. This is because CP prohibits the progress of corrosion. The efficiency of CP is greatly affected by soil properties, geometry of coating defects, and so on. In this survey, all corrosion occurred inside the disbonded coating where CP current could not penetrate[1] and was sufficiently anaerobic for the active growth of SRB.[6] Therefore, the efficiency of CP should be considered together for the precise evaluation of the risk of underground corrosion, and this effect was included as P/S term in the resultant predicting equation.[5]

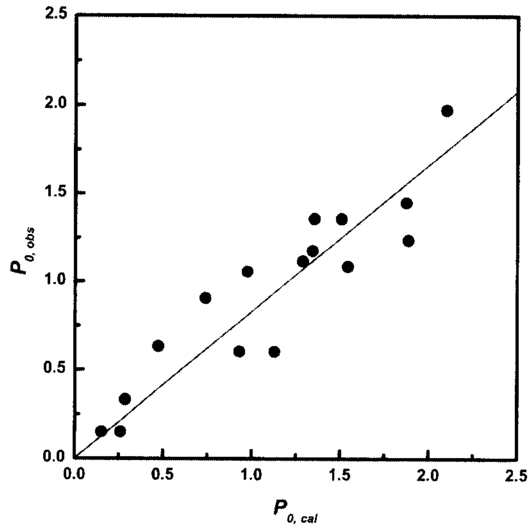

Fig. 6. Relationship between P0 obtained from multiple regression analysis and that obtained from filed survey

4. Conclusions

1) A model has been presented to predict the maximum pit depth on carbon steel pipes in soil environments.

2) The multiple regression model with k in $P=kt^n$ reflecting the environmental actors and n as the regression coefficient has been established.

3) The results showed that the predicting equation explained well the field corrosion phenomena.

4) The underground corrosion is mainly affected by chemical and biochemical properties of soil such as pH, resistivity, reduction-oxidation potential, the level of chloride. However, the efficiency of cathodic protection should be considered together for the precise evaluation of the risk of underground corrosion.

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