New Technology Integration in Environmental Corrosion Survey

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Abstract: Environmental corrosion investigation is an important issue for all kinds of engineering material and construction. Based on the author's 30 year experience in national soil websites, long-distance pipelines, oilfield areas, and marine atmosphere and other corrosion environment surveys, this article introduces the new technology integration of design arrangements, data collection, data analysis and comprehensive evaluation in environmental corrosion survey. It focuses on the design and arrangement of corrosion tests, detection technology, pattern recognition, fractal and other data processing and comprehensive evaluation methods of hazard matrix.

1. Introduction

Environmental corrosion investigation is an important issue for all kinds of engineering material and construction. For more than 30 years, the author has participated in the investigations of soil, atmosphere and seawater corrosions to common industrial materials and the investigations of pipeline and oilfield environment corrosion of petroleum system led by the Ministry of Science and Technology, China. The more important ones are: pre-development investigation of Tarim Oilfield, West-East Gas Pipeline corrosion and stray interference investigation, Shengli Oilfield offshore platform atmospheric corrosion investigation, Zhongyuan Oilfield storage tank corrosion investigation, Dagang oilfield regional environmental corrosion investigation, etc.

Based on the author's 30 year experience in national soil websites, long-distance pipelines, oilfield areas, and marine atmosphere corrosion environment surveys, this article introduces the new technology integration of new methods and ideas in corrosion investigation, and introduces them according to four topics: design arrangement, data collection, data processing and comprehensive evaluation. It focuses on the design and arrangement of corrosion tests, detection technology, pattern recognition, fractal and other data processing and comprehensive evaluation methods of hazard matrix.
2. Design arrangement

2.1 Survey objectives and scopes
The design of the corrosion investigation plan needs to specify the investigated environment (soil, atmosphere, water, oil and gas medium); scopes (geographical location or specific object group); investigation materials (steel, cement, plastic, etc.) and the corrosion information to be understood.

2.2 Test period, number of samples, test location
Corrosion is a random process, and the corrosion statistics for a certain period of time are meaningful. The data [1] gives the formula for the shortest test period:

$$T = \frac{2000}{V}$$  \hspace{1cm} (1)

Where $V$ is corrosion rate of the tested material (average estimated value) in mpy (= 0.0254 mm/a); $T$ is the shortest test time in hours.

The Chinese standard SYJ26-87 stipulates the shortest test $T = 50/V$, where $V$ uses mm/a as the unit (take the estimated value of the corrosion rate in the first 24 hours), and the complete corrosion test preferably includes 5 test cycles.

Considering the periodic changes of the natural environment, the test period of natural embedding is generally not less than 1 year to ensure data reliability.

According to the analysis of soil embedded slice data, the accuracy of the embedded data of 3 parallel test slices is only 70%, which is barely able to understand the corrosion degree of the same material in the same environment; if you want to further compare the data between different materials and different locations, or corrosion modeling and prediction, it is best to take 4-6 parallel coupons [2].

The choice of test site is related to the amount of effective information. The method of evenly distributing dots is often used, and a specific location is added. For example, in the early pipeline survey, evenly distributed points were used, but additional points were added at different soil junctions; special locations such as the bottom of the tank, the top of the tank, and the oil-water boundary layer inside the storage tank also need to be distributed. In the corrosion investigation of Dagang Oilfield, a more advanced clustering method was adopted: based on the soil physical and chemical parameters obtained from the pre-survey, a pedigree clustering analysis was performed on 81 candidate buried points in 17 blocks and 99 wells (stations) of the oilfield, and 23 locations with the most independent information as the formal buried points were selected. This method saves 3/4 of the workload of the embedded slices, and the corrosion information of the unembedded slices can still be obtained through post-data processing [3].

2.3 Design of specific test methods
(1) Comparative test
To compare the corrosion difference of two materials in the same environment, paired comparison or random comparison test can be used. In the former, the two material specimens of the same quantity are paired one by one, and the corrosion difference value of the two material specimens is used as the sample, and the zero difference test is performed; the number of the material specimens in the latter can be different, and t-test is used to check whether the true value is the same. In the corrosion investigation in the Tarim area of Xinjiang, a comparative test was made between two petroleum steels, A3 steel and 16Mn steel. Specimen size 6 cm × 10 cm × 0.8 cm, except for the material differences, the processing conditions are the same. (a) Random comparison: four A3 steel and four 16Mn steel coupons were scattered in each pit; (b) Pairing comparison: one A3 steel and one 16Mn steel coupons were arranged at the same position at the depth of 2 m in the pit.

According to the data analysis of more than 60 embedded slices, the corrosion degree of the two steels in Tarim soil environment is basically the same. However, the corrosion of 16Mn steel is slightly less than that of A3 steel in four buried points, which are related to the high salt content and high bulk density of soil [4].
(2) Study of the relationship between corrosion and time

The National Soil Corrosion website obtains the development law of materials over time through multiple sampling (embedded slices) data. In the past, equal time interval sampling was used. Considering the roughly exponential relationship between the amount of corrosion and time, sampling intervals (equal to corrosion interval) of 1, 3, 5, and 8 (year) was recommend, and more information can be obtained with less sampling times.

Data [2] also introduces the method called Wachter-Treseder, which is that the same material in the same corrosive environment passes through (T+1) cycle, 4 samples are taken, and 5 types of data are obtained. The change rule of material corrosion and environmental corrosivity can be obtained during the test.

(3) Study of the influence and interaction of corrosion factors

Through orthogonal experiment and other methods, the specially designed table is used to arrange the test. See related monographs.

3. Data collection

The data of corrosion investigation come from (1) corrosion embedded film (2) field measurement (3) environmental analysis (4) direct corrosion detection. Corrosion investigation data comes from (1) corrosion embedded slices (2) on-site measurement (3) environmental analysis (4) direct corrosion detection. Among them, the embedding data plays a key role in the success or failure of the corrosion investigation. Because this part of the data is intuitive and credible, but the disadvantage is time-consuming and laborious. The following categories are discussed.

3.1 Corrosion of buried slices

The coupon must be made of a material that can represent the substance to be tested (chemical composition, metallographic structure, surface state, etc.). In the same corrosion investigation, coupons of uniform specifications and uniform processing should be used. Although many standards have stipulated the size of the coupon, it can be flexibly adapted according to the conditions in practical applications. Coupons with the size of 6 cm×10 cm× 0.8 cm or 2.5 cm×5 cm×0.4 cm were often use, and the former is used in wide soil environment, and the latter is used in narrow space (such as the inside of oil and gas storage tank), which can meet the requirements of weight loss detection. The surface of the coupon is coarsely ground to make it uniform, which can improve the data dispersion; in addition, simultaneous burying and simultaneous recycling can also improve the data dispersion.

The coupon burying is divided into natural burying and non-natural burying. The former provides weight loss data, corrosion morphology, corrosion products and other information under natural corrosion conditions, which are all important corrosion information. The latter coupon is buried in a special state. As described below, the steel column of the macro cell corrosion coupon is buried under the electrical connection. The cathodic protection coupon is buried under the electrical connection with the cathodic protection equipment, etc.

(1) Coupon for testing soil macro-corrosion battery

Local soil environmental differences cause macro cell corrosion. When it occurs along the horizontal direction, it causes "long-line corrosion" of the pipeline; it may also occur along the vertical section. During the Tarim corrosion investigation, a 2m long coupon for testing vertical macro cell corrosion was designed: 10 Φ2.5 × 5.0 cm round steel column short stubs connected by steel bars. The surface of the steel column is polished clean and accurately weighed, and it is buried vertically in the excavation pit of the test site. After the test, the steel column was removed, cleaned and the weight loss was calculated. Each steel column represents the corrosiveness of the soil profile at 20 cm intervals. This method found that there are high corrosion areas about 1m underground in the Gobi area of some dry deserts, although the corrosivity of the surface soil layer is close to zero.

(2) Specimen for testing crevice corrosion
The metal in the crevice will accelerate corrosion in a corrosive environment. The gap specimen composed of the test steel sheet and the plastic sheet is placed in the oilfield sewage environment. The test found that the weight loss of X70 steel is greater than that of 16Mn steel under the gap condition; while under the condition of no gaps, the weight loss of 16Mn steel is greater than that of A3 steel [5].

(3) Specimen for testing stress corrosion

There are various test methods for evaluating stress corrosion sensitivity. The simplest method is to force the steel coupon to be bent and then fix it (stress) and bury it in the test environment, and check the crack development of the stressed section after the test.

(4) Cathodic protection inspection sheet

Electrically connect the inspection piece to the cathodic protection facility (pipeline or storage tank), and compare its corrosion status with the naturally buried coupon to obtain the cathodic protection efficiency (protection degree p). In the West-East Gas Pipeline survey, three natural corrosion coupons and three cathodic protection coupons were arranged at the same buried site. Installed on epoxy resin bakelite boards at intervals, of which 1, 3, and 5 are connected to the pipe connection posts of the test pile (under cathodic protection) with cables; 2, 4, and 6 are specimens in the natural corrosion state.

3.2 On-site inspection
(1) Ground detection

Soil resistivity is an important item of environmental corrosion investigation, which is usually measured by the quadrupole method. However, the ordinary ZC-8 meter cannot adapt to the Gobi desert environment, and the detection range can be improved by adjusting the pole distance or adding parallel resistors. The resistivity as high as 1690 Ω/m has been measured in the Tarim Desert.

(2) Inspection in the pit

In the investigation, the depth of the pit where the coupon is buried is generally 1 ~ 1.5 m to simulate the common burying depth of petroleum facilities. The soil is collected in the excavation pit for indoor analysis, and conductivity electrodes, pH electrodes, etc. can also be used for rapid measurement. Five identical steel coupons were used for corrosion investigation in Tarim Basin, and arranged in the vertical or horizontal section of the soil at equal intervals (10 cm) in the upper, lower, left, right, and middle positions. After equilibrating for 20-30 minutes, the potential of the electrode and the maximum potential difference between the four peripheral electrodes and the central electrode can be used as an index of soil homogeneity which reflects the heterogeneity of this unbalanced three-phase mixed system of soil. According to data analysis, among 24 indicators related to soil corrosion, this indicator ranks second in the contribution rate of soil corrosion. The greater the steel potential difference (> 100 mV), the greater the soil corrosivity (> 0.04 mm/a); but the reverse law does not hold.

(3) Physical and chemical properties of soil

The physical and chemical properties of the soil are obtained through samples in the pit. One of the objectives of the corrosion investigation project is to study the corresponding relationship between them and soil corrosivity. The correlation between 24 soil physical and chemical indexes and the importance of corrosion have been analyzed in Tarim corrosion investigation. The correlation coefficient matrix was displayed by the pattern recognition method, and it was found that most of the physical and chemical indexes were clustered into four areas, named resistivity group; buffering group; salt content group and soil / water content group. This is consistent with the conventional understanding that soil corrosion depends on its electrical conductivity, salt content, water content and storage capacity [6].

(4) Rapid detection of corrosivity

Although the investigation of environmental corrosion factors is important, it is better to conduct rapid corrosion detection directly, such as linear polarization probes, resistance corrosion probes, etc. In the corrosion investigation, the following rapid detection technologies have been successfully developed.
(a) Atmospheric corrosion detection battery
In the 1990s, a porous thin-plate gas corrosion detection battery was developed based on the atmospheric corrosion detection cell (ACM). It can quickly convert the corrosivity of ambient gas into battery current output, and the integrated average current of output current $I$ and gas corrosivity $V$ have a good correlation [7].

$$V = 3268 \times \frac{M}{S \times C_t} \times I \times I$$

(2)

Where $M$ is the constants of the probe material, $S$ is the electrode area; $C_t$ is the battery factor. According to the results of our previous experiments, the mean was 0.06 to 0.09.

This sensor and corresponding instruments were used to detect the corrosivity of the gas on the top of the tank in Cangzhou Pumping Station #5, and it was found that the closer the distance from the top of the tank is, the more corrosive the gas is. In addition, the corrosiveness of tank top gas fluctuates tidally with the working conditions of the tank (oil-in and oil-out process), and the maximum corrosion rate is 0.8mm/a, which is about dozens of times of the baseline value.

In the atmospheric corrosion investigation of Chengdao offshore platform in Shengli Oilfield, the atmospheric corrosion battery data and the weightless coupon data are in good agreement. It was found that the outdoor atmospheric corrosion rate of the platform (136.9±23.4 μm/a) is more than 10 times higher than that of the indoor, and the reason is related to the deposition of sea salt on the surface of steel specimen, and the critical relative humidity decreases from 65% to 40% when there is no salt.

(b) Spurious interference detection
In 2007, 210 sets of coupons (6 coupons in each group) were buried along the 4000 km of the West-East Gas Pipeline to obtain corrosion rate of the specimens under both natural conditions and cathodic protection. In addition, the self-developed stray interference detection instrument was used to detect the whole pipeline for many times in September 2008 and April 2009, and the parameters such as pipeline to ground AC potential, pipeline to ground DC potential, coupon DC potential and coupon and pipeline galvanic current were obtained. After data processing, the off potential, off attenuation curve of the coupon, IR drop, pipeline real potential and pipeline polarization potential deviation, etc. can be obtained [8].

Multiple measurements show that there is large AC interference in part of Xinjiang, Gansu-Ningxia junction, Shanxi-Henan junction and Jiangsu, Zhejiang and Shanghai (Wuhu-Maanshan and Zhenjiang, etc.) sections (see Fig.1). The sources of AC interference are various, such as the Gansu section is affected by electrified railways and the Henan section is affected by high-voltage transmission lines, etc.

Fig. 1 Distribution of AC interference on the entire West-East Gas Pipeline (first line) (measured in Apr. 2009)
Measurements in April 2009 showed that stray currents were discharged from some pipe sections in Wuxi, Suzhou, causing severe corrosion of the coupons connected to the pipeline. The reason may be related to the substation equipment in Baihe Town, Shanghai Qingpu, which is the national power transmission from west to East.

(c) Hanging chip resistance probe

Resistance probe (ER) is one of the methods for rapid measurement of environmental corrosion, and there are commercial instruments at home and abroad. Its detection speed is better than that of embedded film, but it is still not fast enough. In 2015, printed circuit technology and a few tenths of a millimeter thin steel sheet was used to make resistance probes to improve detection sensitivity [9]. The resistance of the thin steel sheet and the resistance change (micro-ohm level) of the test sheet sealed in the epoxy resin under the corrosive environment were measured to evaluate the environmental corrosivity. The test shows that the 0.1mm probe can detect the change in 2% NaCl solution within a few hours, and there is good consistency between the test data and the weight loss test in about a week. It is expected that the embedded test can be partially replaced in the Corrosion Investigation of air, water and soil environment to shorten the investigation time.

In addition, a tow electrode is composed of multiple insulated metal wires. According to the maximum potential difference of each wire in the tow electrode, the pitting sensitivity of steel in salt water is evaluated, and it is found that X70 steel has a greater pitting tendency than 16Mn steel.

4. Data analysis

4.1 Conventional methods and special tests

Conventional data processing methods include: correlation analysis, polynomial fitting, multiple linear regression techniques, etc. In addition, the paired test, orthogonal test and other special tests mentioned above need to adopt corresponding treatment methods.

4.2 Mathematical statistical methods

Corrosion is a random process, and it is meaningful only if sufficient data available for mathematical statistics. Most corrosion data can be summarized into four distribution types: normal distribution, lognormal distribution, Poisson distribution and exponential distribution. Only normal distribution corrosion data (such as average corrosion rate) can use mathematical methods such as average value and error analysis.

There are not many opportunities to obtain the complete data of corrosion random variation. Generally, the characteristic data is used for research, such as maximum or minimum value. The corresponding processing method is called extreme value statistics.

The Tarim corrosion survey data conforms to the normal distribution as a whole, but the high corrosion data conforms to the Gumber maximum value distribution. The distribution function formula is used to calculate the proportion of different corrosive soils in the area and the possible maximum soil corrosivity and the probability of occurrence [10]. Using spline function and interpolation method, the specific location of the most corrosive soil in Tarim area can also be obtained.

4.3 Pattern recognition method

Most of the corrosion survey data is neither the complete data of the random process, nor the maximum or minimum data. This kind of data is difficult to deal with by conventional mathematical statistics and probability theory methods. In the 1980s, a statistical pattern recognition method was introduced, and was used principal component analysis (PCA) for the first time in Luning and other pipelines to carry out PCA discrimination of soil corrosion grade classification.

In principal component analysis, the material corrosion index is regarded as the distribution of many corrosion factors in a high-dimensional space. The maximum extension direction is called the first principal component, the second largest extension direction is called the second principal
component, and so on. The components are all linear combinations of the original parameters. Using the first, second, or first and third principal components to display the simplified classification rules. Interface equations instead of visual analysis is used, and improve the corresponding calculation programming to obtain a multi-factor model for judging corrosion levels. Based on the Tarim survey data, several PCA corrosion models have been established [11].

4.4 Fractal method

Pattern recognition has strong data analysis capabilities, but does not involve an understanding of the nature of corrosion. Fractal theory reveals the regularity by studying the deep-level similarities of complex phenomena (processes). The two characteristics of fractal system are: power function and fractal dimension. Through big data analysis of Tarim investigation data, it is found that the mean value and standard deviation of the corrosion rate have good linearity (power function) in the double logarithmic coordinate, and the standard deviation fractal dimension is introduced. The greater the value of the fractal dimension, the greater the discreteness of the data is. As the number of parallel coupons increases, the value of the fractal dimension decreases and stabilizes to 1.343. The standard deviation fractal dimension of the Tarim corrosion survey data is 1.486, and the fluctuation is greater than that of the parallel test because its fluctuation also comes from the soil differences in different regions [14].

With the help of fractal tools, corrosion images can also be treated as numerical data. Through analysis of a large number of experiment data, two-dimensional and three-dimensional fractal dimensions of the corrosion image represent the area and depth distribution fractal dimensions of the corrosion surface pits respectively [15]. Obviously, this helps to alleviate the tedious surface pit measurement work.

It is assumed that the metal surface state in the corrosion process is divided into three types: uncorroded area, corroded area, and corrosion affected area. It is assumed that the corrosion occurrence rates of the three areas are \( p_1 \), \( p_2 \) and \( p_3 \), respectively. By repeating this process with a computer, a predictive model of corrosion development can be obtained. This model involves the deep connotation of corrosion: the ratio of corrosion probability \( p_2/p_1 \) is related to the self-acceleration of corrosion; the ratio \( p_2/p_3 \) is related to the protection ability of corrosion products. The model can quickly provide virtual experimental data according to hypothetical conditions, and then use Monte Carlo method to find the law. This method was used to verify the power function relationship between corrosion rate and standard deviation, the power function model of corrosion development, and the Poisson distribution of the number of pitting. The influence of the boundary of the small coupon on corrosion was also studied.

5. Comprehensive evaluation

The corrosion survey summary report should contain the following evaluation elements:

5.1 Distribution of corrosive grades

In Canglin and Pulin pipeline corrosion investigations, 11 steel coupon burying points and 62 soil physical and chemical properties measuring points were set up. The soil corrosivity was divided into three categories (high > 0.1 mm/a, low < 0.04 mm/a and medium). The PCA prediction was used to obtain the soil corrosion grade distribution along the 400 km pipeline. There was a high soil corrosion area in the 60 km between #53-#62 piles. The pipeline corrosion perforation records over the years also confirmed that most of the perforation locations occurred in this section.

During Dagang Oilfield investigation, 23 burying points and 81 measuring points were set up. Using PCA prediction, a soil corrosion grade distribution map in an area of 3,500 square kilometers was obtained. The soil near the coast is low corrosive, and the high corrosive soil is located far away from the coast. The reason is that the corrosion data comes from 1m underground soil, and the offshore underground soil is saturated with water, and lack of oxygen leads to extremely low corrosion.
Therefore, this conclusion does not apply to surface soils, which are still very corrosive in offshore areas.

5.2 The key factors affecting soil corrosivity and the reliability of discrimination

The investigation found that the three key parameters of soil resistivity, salt content and carbonate content can be used to identify the soil corrosivity along Canglin and Pulin pipelines, and the reliability of the determination is above 90%.

Dagang Oilfield survey found that when the water content exceeds 17% and the resistivity is less than 8 Ω·m, the soil corrosivity is very low, which is different from conventional knowledge. But as mentioned earlier, this conclusion is only for 1.0m underground soil. In addition, the three key parameters of resistivity, water content and salt content can also be used to distinguish soil corrosivity, with an accuracy rate of more than 95% [3].

5.3 Hazard matrix assesses the safety of facilities

According to the survey data of the West-East Gas Pipeline, the corrosion rate of the naturally buried inspection piece Vs (considered as soil corrosion) is taken as the abscissa; the non-protection degree of cathodic protection is taken as the ordinate.

The non-protection degree of cathodic protection is defined as (1-protection degree), namely:

\[ 1-P = \frac{V_{CP}}{V_S} \]  

The \( V_{CP} \) is the corrosion rate of the protection coupon.

According to the classification of soil corrosion in China: high (> 0.064 mm/a), medium (0.02~0.064 mm/a) and low (< 0.02 mm/a).

Non-protection degree is also divided three categories: poor (non-protection degree > 0.6 or protection degree < 40%), medium (protection degree 40 ~ 80%) and good (non-protection degree < 0.2 or protection degree > 80%). Then, a 3×3 criticality matrix was obtained, as shown in Fig. 2.

![Fig. 2 Hazard matrix of the survey data of the West-East Gas Pipeline](image)

According to the investigation, there are four highest risk pipeline V sections along the West-East Gas Pipeline: Gansu #32, Shanghai-Jiangsu-Zhejiang #135, #137, and Lu straight, which the corrosion rate under cathodic protection still exceeds 0.1mm/A, and needs to be treated immediately. There are 16 sub high risk IV pipe sections, and the risk comes from strong environmental corrosivity or poor cathodic protection, which requires targeted and planned maintenance schedule.

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