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Research on buried pipe corrosion assessment using corrosion sensors

Hidefumi Itaya, Kazuyuki Midorikawa, Takaaki Nagai and Shukuji Asakura

ABSTRACT

This research aims to establish a water pipeline replacement plan that employs soil-corrosion evaluation technology and utilizes easy-to-use corrosion sensors by assessing the performances and validating operation methods based on verification experiments. Since 2005, we have assessed the performances of two different types of sensor, and have confirmed that bar-type sensors can detect soil corrosion effects, including macrocell corrosion. To verify the sensors' practicality, beginning in 2007 we have performed tests on corrosion sensors buried underground for two pipelines with nominal diameters 400 mm or more. In 2008, we collected and analysed the data from some of the sensors, which were buried for about a year. This paper discusses the results of the corrosion sensor performance assessment to date and the practicality of sensors based on data analyses of the test sensors collected in 2008.

Key words | corrosion sensor, electrical resistance method, macrocell corrosion, marine clay, soil corrosion, water pipeline

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INTRODUCTION

Background and purpose

On 16 June 2005, a hole with a 5 cm diameter was found in the bottom of a ductile cast iron pipe with a nominal diameter of 800 mm (Tomioka Line; Figure 1), even though the pipe was still within the legally defined life period. The pipeline, built in 1970, was not covered with a polyethylene sleeve, and 950 households in Yokohama city suffered interruption of water supply for eight hours. This led to the convening of the Yokohama Yokodai water pipe leakage investigation committee, which included outside specialists, to discuss the cause of the accident as well as preventive measures. Upon examining the pipe and soil corrosiveness, it was revealed that although the pipe maintained the same material quality standard as when it was initially installed, the bottom of the pipe, in particular, was badly corroded.

Moreover, the soil around the bottom of the pipe, which caused the water leakage, showed strong corrosiveness. The macrocell corrosion effect by corrosive soil (marine clay) was confirmed upon examination. The committee proposed that a simple and cost-effective method to examine the corrosiveness of the soil in the city be studied as part of the replacement plan to achieve the best results.

Yokohama has been replacing water pipes installed in corrosive soils (marine clay) within large-scale developed land, because the city acknowledges that the large-scale land development has caused the marine clay layer to appear close to the ground surface, as indicated in Figure 2.

More corrosive pipelines are given priority by a test drill before replacement to determine corrosiveness. The purpose of our research is to develop easy-to-use corrosion sensors that can assess soil corrosiveness of the site as well as contribute to a water pipeline replacement plan by assessing performances and verifying operation methods based on test experiments.

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Figure 1 | Tomioka line pipe.

Direction of research

The research aims to develop simplified methods that allow soil corrosiveness in the city to be investigated. Because our research involves developing new technologies, we have employed a three-phase test to achieve this goal with an emphasis on the following:

- Macrocell corrosion effect.
- Materials and shapes of corrosion sensors.
- Practicality of corrosion sensors.

During the first phase, we confirmed that the macrocell corrosion effect is a phenomenon that can occur anywhere, and is not exclusive to the Yokodai water pipe leakage case. In the second phase, we ascertained the corrosion conditions and developed the material and shape of the corrosion sensors to meet these conditions. The third phase aims to verify the practicality of the corrosion sensors.

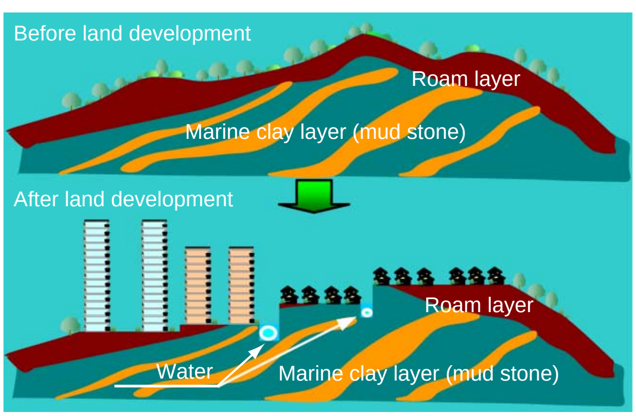

Figure 2 | Large-scale land development.

Figure 3 depicts the relations between the direction of our research and each test phase, which will be described below.

METHODS

We are employing three-phase tests on sensors with different shapes using various burial methods to assess performances and to verify operation methods. In the verification test, we initially checked for macrocell corrosion in the pipes being used. In the second phase, we simultaneously evaluated the material, shape and performance of the sensors. Next, to verify the practicality of the corrosion sensors, we buried sensors for mid- and long-term data collection. The tests are described below.

Verification test

In this research, we examined the actual corrosion conditions, and assessed the performances of the test sensors before installing them in the pipes that are being used.

Chip-type soil corrosion sensor

This test aimed to determine the cause of Yokodai water pipe leakage as well as to verify the corrosion assessment method for soil environments using the metal test sensor. The test sensor was made by cutting normal steel into a cone chip to be buried in the actual soil environment as a corrosion sensor. The sensors were fabricated and buried in 2005. Then they were collected for analysis of corrosion rates. Table 1 shows the test sites and test implementation periods.

Figure 4 shows a test sensor, which consisted of normal steel round bar with the tip cut into a conical shape (dimensions: diameter 10 mm, cone part length 40 mm, cylinder part length 10 mm). These dimensions were selected to accurately analyse soil corrosiveness using precision balance measurements. This test sensor was connected to the tip of the fibre-reinforced plastic bar to be buried for the test.

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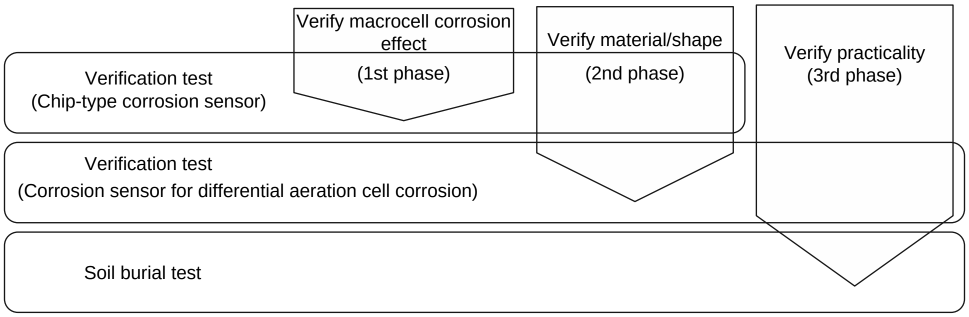

Figure 3 | Relations between the direction of our research and each test.

Figure 5 illustrates the positions of the buried test sensors. Five sensors were buried either above or below the pipe at the test site. A valve chest was provided at the upper part of the test site to collect the test sensors, and a PVC pipe was installed as a guide pipe. The following was performed as part of the test. As the sensors were buried, the soil was visually inspected. Then, amperometry on macrocell corrosion was performed while the sensors were underground. After the sensors were collected, the average and highest corrosion rates were measured.

Corrosion sensors for differential aeration cell corrosion

This test was conducted after the verification test of the chip-type soil corrosion sensor in 2006. We used test sensors that allowed evaluation of the macrocell corrosion effect due to the differential aeration cells as well as the soil corrosiveness. For the second and third phases of this research, which aim to verify the performance and practicality of the sensors, we buried test sensors in normal soil and corrosive soil. Table 2 shows the test sites and test implementation periods.

Figure 6 shows the three types of test sensor, a round bar, pipe and segmented electrode, which are described below and in Table 3.

Table 1 | Test sites and implementation of the tests

Test site	Sensors buried	Sensors collected	Period
A	17 February 2006	23 October 2006	248 days
B	21 February 2006	25 October 2006	246 days
C	17 March 2006	26 October 2006	223 days
D	2 March 2006	27 October 2006	239 days

Bar type

The 30 cm polished round bar was made from normal steel (SGD 400: diameter 2 cm).

Pipe type

The pipe sensor was made from a black pipe (SGP, 15A: O.D. 21.7 mm, thickness 2.8 mm) using the following procedure. First the outer circumference was machined by a lathe to obtain a 2 cm diameter. Then the mill scale on the pipe surface was removed to obtain O.D. 2 cm. Finally the pipe was cut to a length of 30 cm to be used as the test sensor.

Segmented electrode

Figure 7 shows the segmented electrode test sensor, which consisted of five steel pipes (O.D. 2 cm, length 4 cm, each) cut out of black pipe (SGP, 15A). We used a PVC pipe to put the five steel pipes through the axle to fix with acryl discs (thickness 1 mm) inserted between the steel pipes for insulation. The conducting wires from the steel pipes were pulled and connected so they could serve as a piece of steel pipe. By measuring the electrical current using the segmented electrode, we could confirm whether macrocell corrosion occurred.

The test sensors were buried by creating a valve chest. To remove the sensors after the test, PVC pipes were used as guides and vinyl-coated stainless wires were attached to the test sensors to be drawn from the upper part of the pipes (Figure 8). The following was performed as part of the test. As the sensors were buried, the soil was visually inspected. Then amperometry on macrocell corrosion was performed

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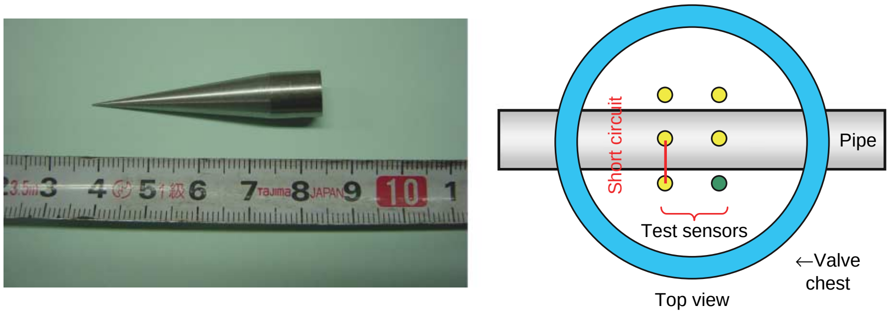

Figure 4 | Chip-type test sensor.

while the sensors were underground. After the sensors were collected, the average and highest corrosion rates were measured.

Underground test

Overview

Because these sensors are likely to serve as a new soil corrosion evaluation method, we conducted verification tests. As part of the third phase, we examined both the operation method and the accuracy of the corrosion sensors with an emphasis on verifying the practicality of the method. We chose pipelines in areas where the City of Yokohama has been conducting countermeasures against corrosive soils. We buried several test sensors near underground pipes with the intent of collecting them all in 5 to 10 years. However, periodically collecting some of test sensors and analysing the progression of corrosion should allow the corrosive conditions of the pipes to be indirectly estimated. This information will aid in determining the soundness of the pipes as well as deciding which pipes should be replaced after the control period.

The third-phase test began in 2007, when the test sensors were buried. In 2008, some of these test sensors were collected for analyses and others were buried in different test sites. The test will continue so that the test sensors are collected on a regular basis and other test sensors are buried in different test sites. Herein we discuss the test sensors buried in 2007 and the results of the analyses for the sensors collected in 2008. Because we need to investigate distribution mains (nominal diameter 400 mm or more), we chose two 1-km water pipelines, for which the City of Yokohama has been performing countermeasures against soil corrosion.

The test sensors were buried in valve chests at 100-m intervals in 11 locations along a pipeline. Figure 9 depicts the two types of valve chest. Each large valve chest contained six test sensors whereas each small valve chest contained a single sensor. To measure the degree of corrosion, a sensor from the large valve chests is to be removed every one to two years. The test sensors in the small valve chests are buried as backup in case the test sensors in the large valve chest have abnormal values.

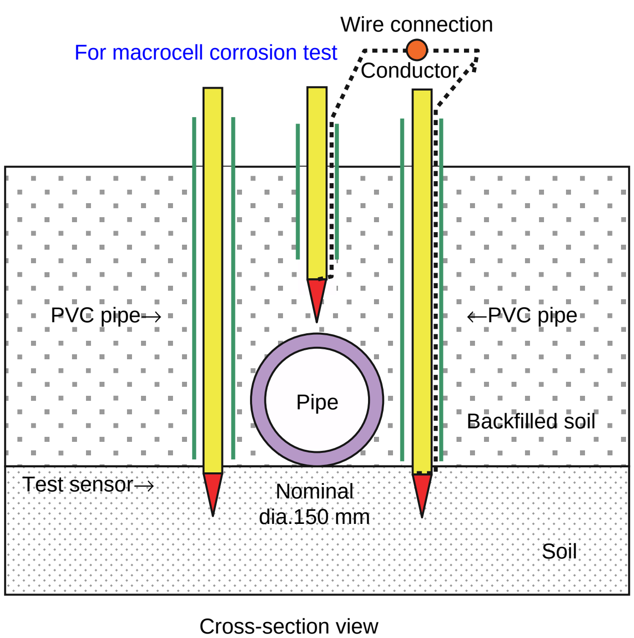

Figure 5 | Buried test sensors.

Test sensors

Two types of test sensor were used for the test: one for monitoring and the other for scrutiny. A test sensor for

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Table 2 | Test sites and implementation of the tests

Test site	Soil	Sensors buried	Sensors collected	Period
E	Normal soil	7 August 2006	31 January 2007	177 days
F	Corrosive soil	10 August 2006	29 January 2007	172 days
G	Corrosive soil	11 August 2006	1 February 2007	174 days
H	Normal soil	21 August 2006	5 February 2007	168 days
I	Corrosive soil	22 August 2006	6 February 2007	168 days
J	Corrosive soil	23 August 2006	7 February 2007	168 days

monitoring was used to visually inspect the progression of corrosion from above ground at regular intervals. If an abnormality is confirmed, the sensor for scrutiny is pulled out of the ground to accurately confirm the degree of corrosion.

The test sensor for scrutiny was made by cutting a round bar (FCD400, diameter 18 mm; Figure 10) to fit the nominal diameter of the target pipeline. Instead of normal steel, which was used in the verification test, ductile cast iron was used for the sensor because ductile cast iron is more adaptable to the environment where the water pipes were buried. To provide a more accurate measurement using a precision balance, the test sensor, which is an improved form of the round bar type test sensor used in the verification test, was devised to allow only the tip of the sensor where corrosion tends to concentrate to be removed.

For this test sensor, a test piece of ductile cast iron cut out of FCD400 was mounted in the tip of a stainless round bar (Figure 11). When buried in corrosive soil, the thickness of the test piece decreases as corrosion progresses, which results in a change in electrical resistance. Thus, the change in electrical resistance can measure the degree of corrosion. (This method is called the electrical resistance method; the electrode for this method is commercially available.)

Because the corrosion rate of the test piece mounted in the electrode bar depends on the corrosiveness of the soil surrounding the bar, the sensor can be used to measure the corrosiveness of the soil. By placing the conducting wire from the test piece in close proximity to the ground surface at the site, the electrical resistance can be measured on the ground to evaluate the degree of corrosion without having to remove the test sensor. The ability to measure the degree of corrosion without having to necessarily drill or collect the sensor should reduce costs when installing them, not only along distribution mains but along water pipes throughout the city.

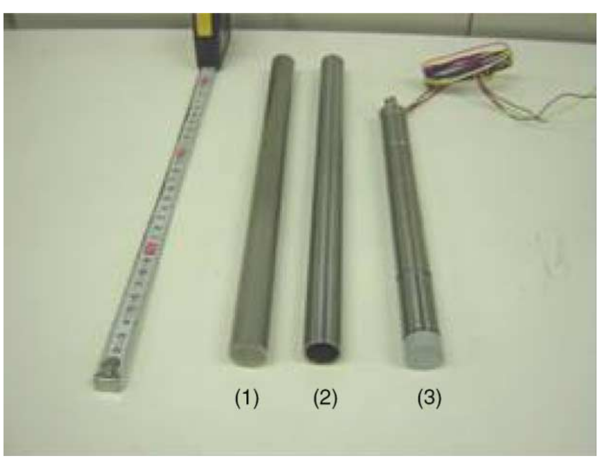

Figure 6 | Round bar test sensors.

Burying test sensors

The test sensors were buried in the same manner as the corrosion sensor for differential aeration cell corrosion, except special drilling was required for sensors that simultaneously examined soil and pipe corrosion. Figure 12 illustrates the test sensors where six test sensors were buried in a large valve chest. Figure 12 is also applicable to burying a small valve chest, except only one sensor is used. Five test sensors for scrutiny and a test sensor for monitoring were buried in the large valve chest; both sensors were buried alternately in the small valve chests. The test sensors for scrutiny in the large valve chest are to be collected at regular intervals to observe changes over the years.

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Table 3 | Three types of test sensor

	Shape	Length	Diameter	Steel material
(1)	Bar	30 cm	2 cm	SGD400 Polish bar
(2)	Pipe	30 cm	2 cm	SGP Black pipe
(3)	Segmented electrode	24.5 cm	2 cm	SGP Black pipe

Test items

Data from the test includes: measurements of the initial values before the test sensors are buried, periodic collection of the monitors for scrutiny, and resistance measurements of the sensors for monitoring.

Burying the test sensors

When burying the test sensors, the entire circumference of the pipe should be exposed to measure the corrosion rate of the pipeline being used so that the results can be compared with the corrosion rates of the test monitors for scrutiny. The corroded pores can be measured with a depth gauge. Additionally, the soil at the site should be examined (five items of American National Standards Institute (ANSI, sump water).

Collecting the test sensors for scrutiny and after collection

Once the test sensors have been collected, the resistance values of the test sensors for monitoring should be measured using the electrical resistance method, and their corrosion rates should be analysed using the weight reduction method.

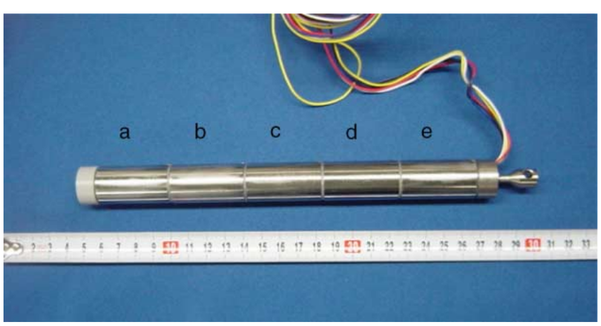

Figure 7 | Segmented electrode.

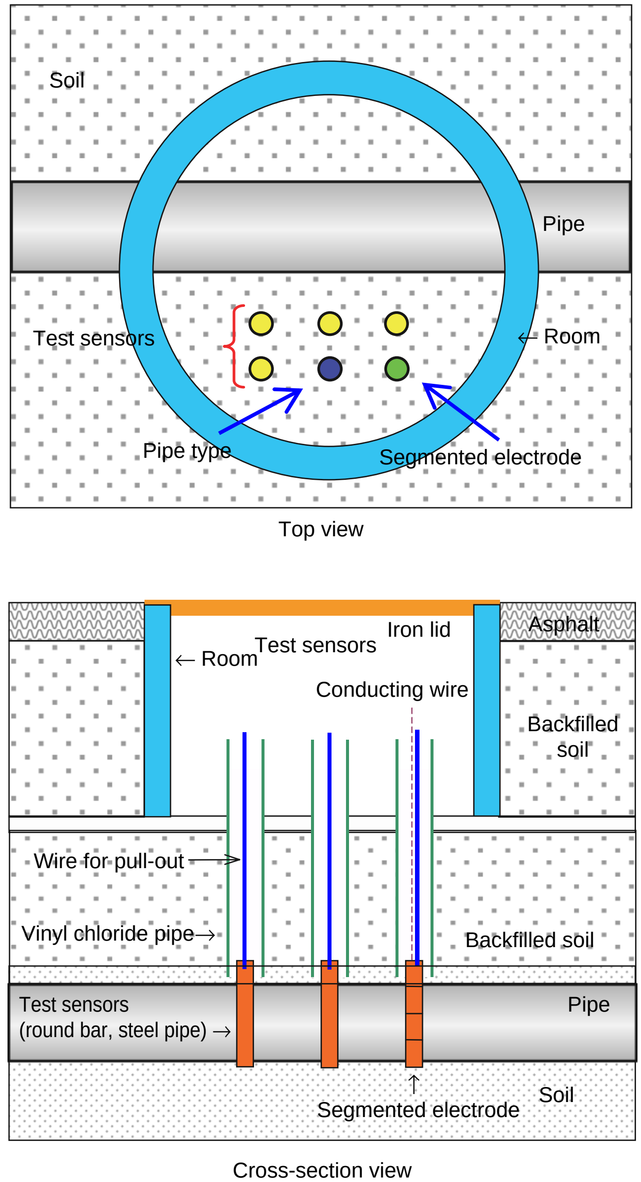

Figure 8 | Test sensors underground.

RESULTS AND DISCUSSION

Verification experiment

Chip-type soil corrosion sensor

For the chip-type test sensors buried in the test, the weight reduction for all the test sensors was measured using a precision balance to obtain the average corrosion rate (Equation (1)). In addition, for the test sensors with

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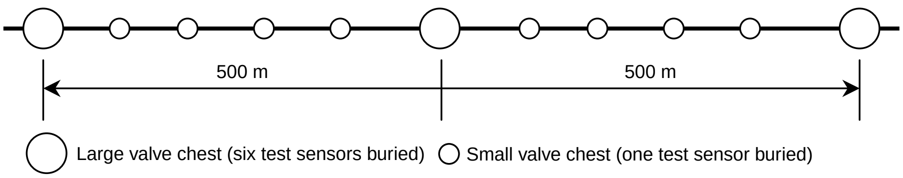

Figure 9 | Spots where test sensors were buried.

confirmed intensive corrosion, the largest depth of the corroded pore was measured, which was converted to the largest corrosion rate (Equation (2)). Next, corrosion rates were calculated from the macrocell corrosion current measured prior to being buried, while underground, and once collected (Equations (3) and (4)). The macrocell corrosion currents were measured by connecting the wired conductor (shown in Figure 5) to an ammeter. Table 4 shows the test results. The equations used to determine the values are described below.

$$\text{Average corrosion rate (mm/year)} = \frac{\text{Weight reduction amount (g per 1 cm)} \times 10\,(\text{mm cm}^{-1})}{7.86\,(\text{g/cm}^3,\ \text{iron density}),\ \text{circumferential area (cm}^2\text{per 1 cm) days underground}} \times 365\ \text{days} \quad (1)$$

$$\text{Highest progression degree of corrosion pores} = \frac{\text{largest depth of corrosion pores (mm)}}{\text{days underground}} \times 365\ \text{days} \quad (2)$$

$$\text{Corrosion current density } (\mu\text{A cm}^{-2}) = \frac{\text{Average microcell corrosion current } (\mu\text{A})}{\text{Surface area of test piece } (31.4\ \text{cm}^2)} \quad (3)$$

$$\text{Reduction formula of Fe corrosion rate}: 10\,\mu\text{A cm}^{-2} = 0.116\ \text{mm/year} \quad (4)$$

Table 4 revealed the following:

- Test site B has the highest corrosiveness. Although the average corrosion rate and highest corrosion rate of test site B are similar those of the other sites (except for test site C), Test site B shows partial corrosion, resulting in the highest corrosiveness. The highest degree of corroded pores is 0.56 mm/year, which is about 10 times the average corrosion rate of 0.045 mm/year. In addition, corrosiveness seems extremely high in soil environments where corrosion tends to occur locally, as witnessed by the Yokodai water pipe leakage case caused by the corroded through-bores in the water pipe.
- Test site A shows the highest macrocell corrosion current. The site consists of extremely hard mud layers on the bottom of the pipes and backfilled soil, which are

Figure 10 | Test sensor for scrutiny.

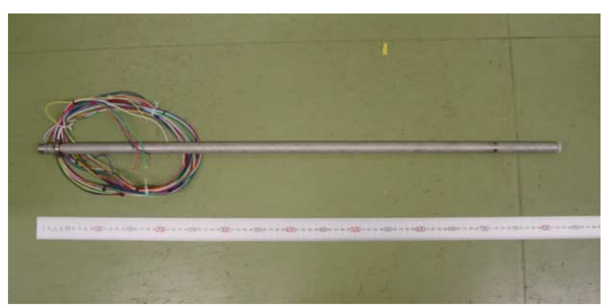

Figure 11 | Test sensor for monitoring.

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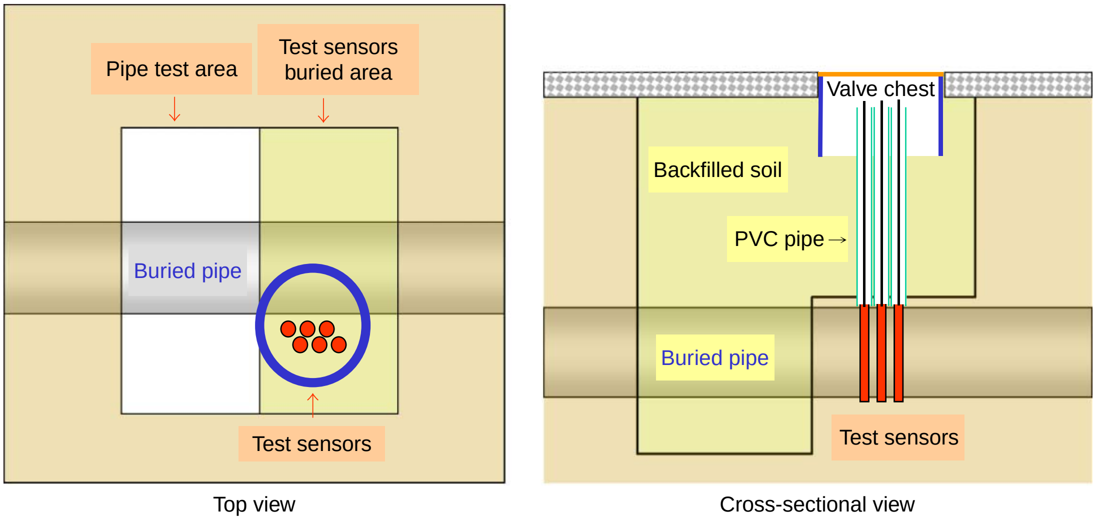

Figure 12 | Test sensors underground.

both quite normal. Owing to the difference in soil quality, macrocell corrosion is likely. The test revealed that corrosion is predominant and due to the difference in the soil quality.

The aforementioned results can be summarized in the following two points.

- The difference in soil quality causes macrocell corrosion where the bottom of the pipe becomes the anode and the top acts as the cathode.
- When partial corrosion occurs, corrosion with the potential to cause through-bores in the pipe is likely to progress in an environment where a macrocell corrosion will not be formed by the difference in the soil quality, even within the legally defined life period.

Considering these factors, a corrosion sensor must be able to diagnose partial corrosion and macrocell corrosion, which will cause the bottom of the pipe to become the anode. A metal corrosion sensor that can directly provide these diagnostics when buried underground will be effective.

Corrosion sensor for differential aeration cell corrosion

We evaluated whether macrocell corrosion occurred during the macrocell corrosion current measurement using the segmented electrodes buried in the test. At the same time, we measured the weight reduction amount of the bar-type test sensor using a precision balance after dividing the sensor into six parts using a band saw to obtain the corrosion rates. Then we evaluated each test sensor.

We measured the macrocell corrosion currents at each test site using the segmented electrodes to check for macrocell corrosion. Table 5 shows the results. Sign indicates the current direction: ' + ' cathode, ' − ' anode. Test site J has an absolute value of the current measured in steel

Table 4 | Relations between the corrosion rates of test sensors and the type of soil

	Equation	A	B	C	D
Average corrosion rate	1	0.041 mm/year	0.045 mm/year	0.014 mm/year	0.056 mm/year
Highest progression degree of corrosion pores	2	–	0.56 mm/year	–	–
Macrocell corrosion current	3	5.6 $\mu A\,cm^{-2}$	0.57 $\mu A\,cm^{-2}$	0.033 $\mu A\,cm^{-2}$	-1.2 $\mu A\,cm^{-2}$
Corrosion rate resulted from macrocell corrosion	4	0.065 mm/year	None	None	0.014 mm/year
Corrosion mode		Whole area corrosion	Partial corrosion	Whole area corrosion	Whole area corrosion

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Table 5 | Macrocell corrosion current at each test site (μA)

Steel pipe measured	Depth	E	F	G	H	I*	J
e	Shallow	10	0	8	4	(45)	17
d	↑	1	−6	−4	2	(−11)	22
c		−10	−6	−2	−3	(−11)	30
b	↓	−2	0	4	−3	(−11)	−12
a	Deep	−1	12	−6	−1	(−14)	−58
Macrocell corrosion		None	None	None	None	Not confirmable	Confirmed

*Test site I is shown as a reference because the measurement values of the current were unstable.

pipe 'a' of 58 μA, the highest in the segmented electrode buried. The minus sign indicates anodes, and 'c', 'd' and 'e', which are on the upper side of the segmented electrode in terms of depth, became cathodes, thus facilitating the corrosion of 'a'. The results indicate that a typical differential aeration cell, which can form in the direction of depth, occurred, resulting in macrocell corrosion at test site J.

We then compared the results with those of the round bar test sensor buried at test site J. Figure 13 describes the distribution of the corrosion rates. Corrosion is facilitated in the bar pipes, which are the same parts as those of the steel pipes that became the anodes (Table 5). The results demonstrate that the round bar-type test sensor can evaluate soil corrosion, including the macrocell corrosion effect. Additionally, the segmented electrode type sensor can be an effective measure to evaluate macrocell corrosion. Thus, the test verifies that the sensor can detect soil corrosion as well as macrocell corrosion occurring locally after a short burial time.

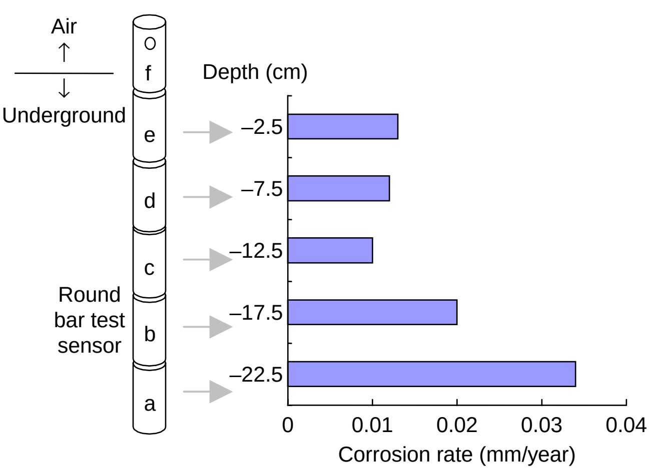

Figure 13 | Relations between depth underground and corrosion rate (test site J).

Burial test

In 2007, we examined the pipes and buried the test sensors, which were collected for the first time in 2008. Based on the examination of the pipes conducted in 2007 and the analysis results of the test sensors in 2008, we evaluated the burial environments of two water pipelines. Moreover, to evaluate the performances of the corrosion sensors, the corrosion rates in the same soil were measured using different methods. Initially, we intended to perform a burial test at pipeline A and pipeline B, but severe corrosion was confirmed at pipeline B after drilling. Thus, we switched the test to pipeline C. This is why pipeline B is a single data point.

Corrosion rate by pipeline

Figure 14 shows the actual measured values for corrosion rates based on the examination of the pipes, while Figure 15 shows the estimated results of the corrosion rates by the electrical resistance method using test sensors.

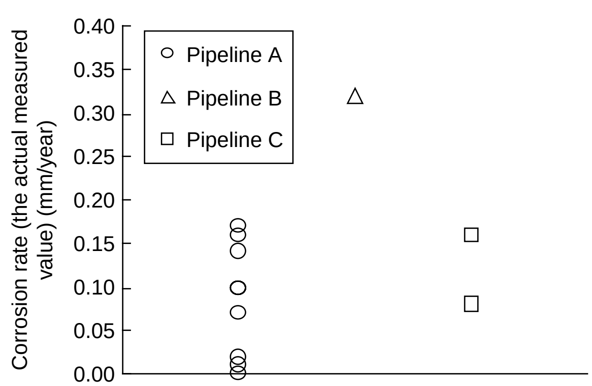

Figure 14 | Corrosion rates based on the actual measured values.

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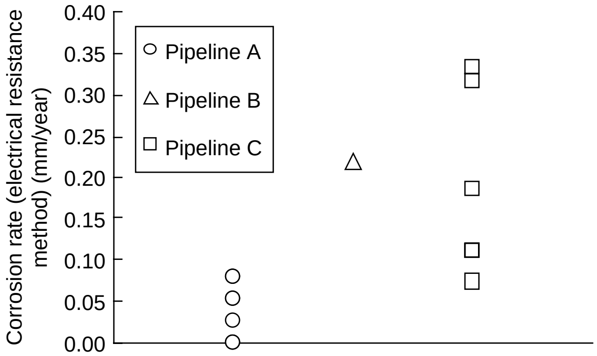

Figure 15 | Corrosion rates by the electrical resistance method.

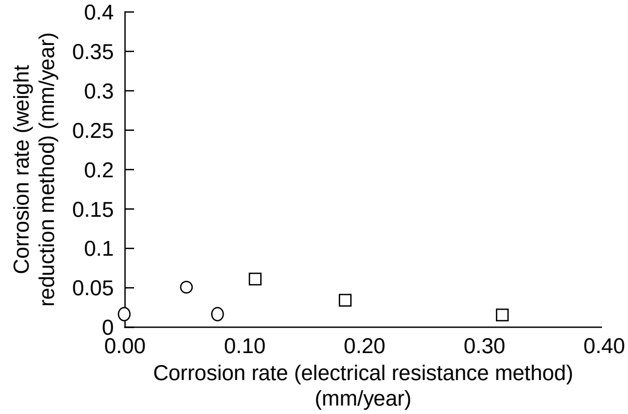

Figure 17 | Correlation between the electrical resistance method and weight reduction method.

The corrosion rates (actual measured values) indicated in Figure 14 were obtained from the largest depth of corrosion of the pipe divided by the burial period. Pipelines A, B and C were examined at 11, 1 and 3 points, respectively.

In these examinations, pipeline B, which had the severest corrosion, shows the highest corrosion rate, while some parts of pipelines A and C have a corrosion rate of about 0.2 mm/year. Considering the legally defined life of the pipeline is 40 years, the risk of corrosion in soils is high and the pipelines must be replaced as a priority because through-bores can form in these pipes within the legally defined life period.

Next, to estimate the corrosion rate by the electrical resistance method, we examined pipelines A, B and C at 7, 1 and 6 points, respectively. As shown in Figure 15, pipeline B had a corrosion rate of 0.22 mm/year and the 7 points in pipeline A, had an average of 0.19 mm/year. These results confirm the necessity to replace these pipes.

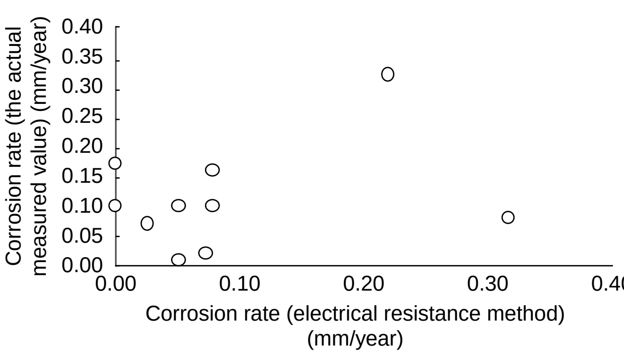

Figure 16 | Correlation between the electrical resistance method and the actual measured values.

Corrosion evaluation by measurement points

To evaluate the performances of the two types of corrosion sensor, we compared the electrical resistance method using test sensors for monitoring (Figure 16) and the weight reduction method using the test sensor for scrutiny (Figure 17) with the actual measured values by examining the pipes. Because both test sensors were exposed to the same environment as the underground pipes, we expected them to be correlated. However, there does not seem to be a definite correlation between them at the present time. This low correlation may be due to difficulties in detecting thickness reduction amounts less than 0.1 mm using resistance change. The value based on observations is estimated from the result found in Figure 14, and suggests that most of the corrosion rates of the pipelines are less than 0.1 mm/year. Therefore, we will continue to investigate the validity of the corrosion evaluation for each measurement method by examining the correlations based on long-term test results.

However, we regard these methods as effective. When the actual measured value was 0.32 mm/year, the electrical resistance method had a similar value.

CONCLUSIONS

About corrosion sensors

In this article we discussed the research results concerning direct diagnostic methods of soil corrosiveness

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(corrosion sensors) by burying test sensors. The corrosion sensors are designed to accurately diagnose the corrosiveness of soil environments that affect pipelines. Additionally, we considered the capability of the sensors to obtain information regarding macrocell corrosion and local corrosion, which are valuable when considering previous pipeline corrosion cases. Moreover, cost efficiency is indispensable in order to provide numerous corrosion sensors at each pipeline.

Although we initially created a corrosion sensor from a cone-shape metal piece, we are now considering employing two types of corrosion sensor to obtain the corrosion rate: one to measure the weight reduction amounts and one that utilizes changes in electrical resistance. Our research has revealed the following:

- Actual environment testing confirmed that using a bar-type test sensor with the same nominal diameter as the pipeline allows soil corrosiveness to be assessed and macrocell corrosion to be detected.
- To efficiently and continuously measure soil corrosiveness, we developed a prototype of a sensor that can evaluate corrosiveness without being collected.

Because the sensors were buried less than a year ago, the capabilities have yet to be demonstrated as the correlation with corrosion rates obtained from the pipes has not been confirmed, except for the one buried in highly corrosive soil where the estimated results agreed well with the obtained value. Our research has been based on the idea of realizing a simplified method to assess soil corrosiveness. We will continue to collect data from the sensors, while continuing with the round bar-type test sensors, which have already been demonstrated to be effective in the verification tests.

Future development

Accumulating data while simultaneously providing prompt practical applications is indispensable in the examination of soil. To create more accurate, cost-efficient corrosion sensors, we will continue research and development by selecting distribution mains and burying test sensors along them. Additionally, we strive to improve the accuracy in estimating the corrosion rate by employing the electrical resistance method beginning in 2009.

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