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Effect of Applied Voltage on the Reliability of Coating Flaw Detection of Pipe with Different Buried Depths

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External corrosion control of buried pipe can be achieved by the combination of barrier coating and cathodic protection. Coating damage and deterioration can be induced by many reasons; damage during handling and laying, enhanced failure at low temperatures, failure during commissioning and operation, disbanding due to inadequate surface cleaning, rock penetration during installation and service etc. This work focused on the effect of survey conditions on the reliability of coating flaw detection of buried pipes. The effects of applied voltage and anode location on the detection reliability of coating flaw of buried pipe in soil with the resistivity of *ca.* 25.8 kΩ·cm were discussed. Higher applied voltage increased the detection reliability, regardless of buried depth, but deeper burial depth reduced the reliability. The location of the anode has influenced on the detection reliability. This behaviour may be induced by the variation of current distribution by the applied voltage and buried depth. From the relationship between the applied voltage and reliability, the needed detection potential to get a desire detection reliability can be calculated to get 100% detection reliability using the derived equation.

Keywords: *Buried pipe, Coating flaw detection, Buried depth, Detection potential, Reliability*

1. Introduction

External corrosion control of buried pipe can be achieved by the combination of barrier coating and cathodic protection. Cathodic protection by impressed-current or sacrificial anode methods applied the current flows to coating defects that exposed steel and through the undamaged coating [1-4]. However, coating damage and deterioration would be induced by many reasons; damage during handling and laying, enhanced failure at low temperatures, failure during commissioning and operation, disbanding due to inadequate surface cleaning, rock penetration during installation and service, lack of coating integrity at elevated temperature, disbanding through pipe movement and lack of adhesion etc. [5-9].

Therefore, several electrical surveys are used to examine the performance of both coating and cathodic protection where corrosion occurs [10-13]. Generally, indirect assessment of external corrosion of pipe has been undertaken as a 2 step process using a close interval potential survey (CIPS) performed to determine the level of cathodic polarization and a direct current voltage gradient (DCVG) survey to determine the location of coating defects [14-19]. Usually, two techniques are used separately, but there are several advantages to undertaking a combined CIPS and DCVG survey [20]. Both surveys are performed at the same time by the same surveyors, under the same climatic and soil conditions. A further advantage can be obtained by two surveyors walking over the pipeline [21]. However, in a power plant, the earth current measured between two reference electrodes placed on the ground will only indicate the relative magnitude of the DC moving in the ground between the two electrode positions [22-24]. Where this current is going to, or coming from can't be determined. To solve these limitations, the area potential and earth current (APEC) survey was recently proposed [25]. This method uses 3 reference electrodes.

Gas pipelines were usually buried at a constant depth in the soil, but the pipelines in nuclear power plants were buried with different depth and multiple layers. Therefore, detection reliability for coating flaws in nuclear power plants was low and thus detail survey conditions are needed. As described above, three kinds of survey method have an advantage and a disadvantage. Many researchers

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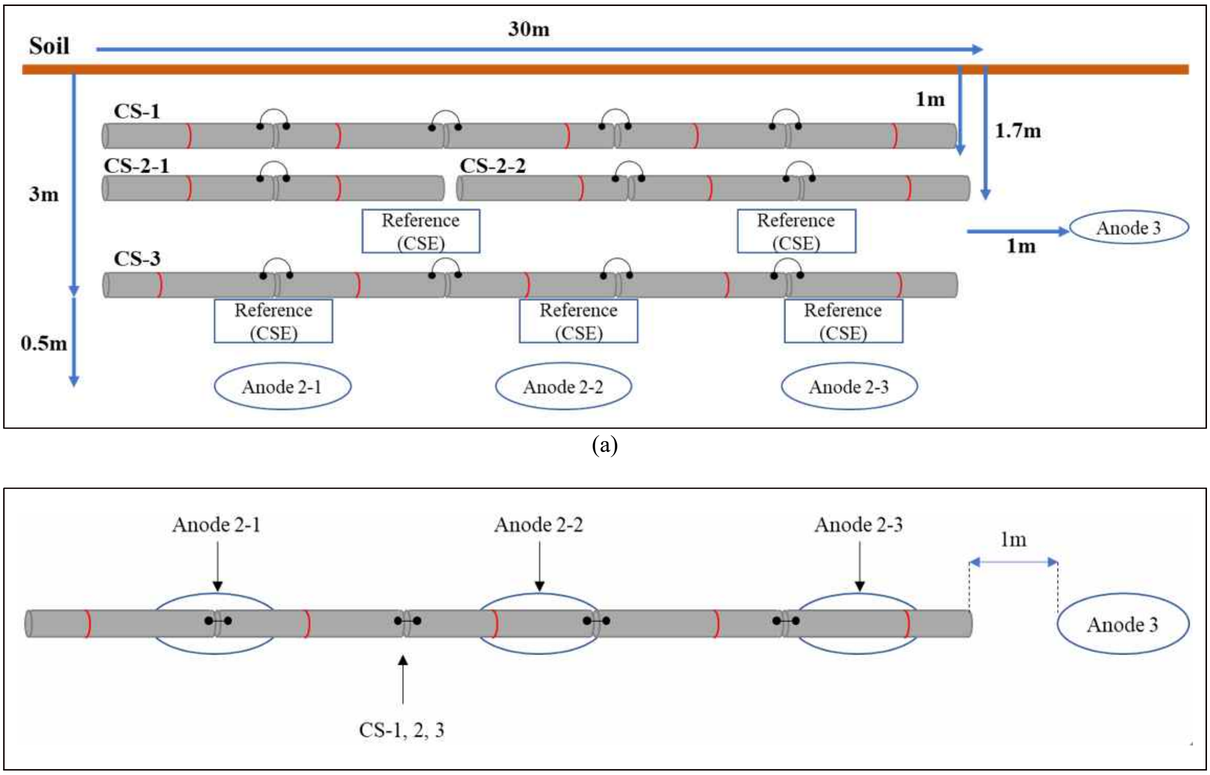
Table 1 Buried pipes and flaws in the test bed

Pipe[*]	Buried depth (m)	Diameter (cm)	Length (m)	Total Surface Area (cm^2)	Total Flaw Area (cm^2)	Flaw ratio (%)
CS-1	1.0	10	30	94,245	2,825	3
CS-2-1	1.7	10	12	37,698	1,130	3
CS-2-2	1.7	10	18	56,547	1,695	3
CS-3	3.0	10	30	94,245	2,825	3

*CS (Polyken coated carbon steel)



(a)

(b)

Fig. 1 Configuration of buried pipes in test bed (Red lines were the coating flaws); (a) side view on the test bed (polyken coated carbon steel pipes), (b) top view on the test bed.

recently reported the protection performance simulation of coated pipe using FEM method [26], the analysis of damage detectability in buried pipes with 3D FEM [27], and the real-time corrosion control system of buried pipes [28], but there is little about the research on the survey condition to detect the coating flaws.

Therefore, this work focused on the effect of survey conditions on the reliability of coating flaw detection of buried pipes. Test bed with 3 layered pipelines was constructed, and cathodic protection system was real-time monitored. The material of buried pipe was one kind of ‘polyken coated steel pipe (CS)’ , The buried depths of pipes were from 1 to 3 meters depending the design purpose. In every pipe, coating flaws were intentionally formed. The effects of applied voltage and anode location on the detection reliability of coating flaw on buried pipe in soil were discussed.

2. Experimental Methods

2.1 Set-up of test bed

Fig. 1 shows the configuration of buried pipes in test bed. In the figures, red lines on the pipes imply the position of the coating flaws. Fig. 1a depicts the side view

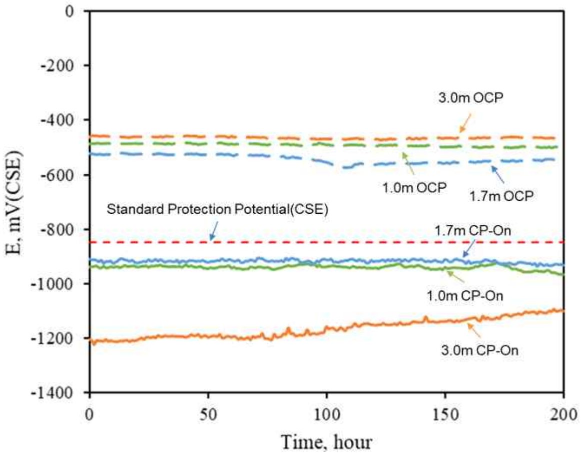


Fig. 2 Monitored results on the open circuit potentials and the protection potentials of CS pipes (buried depth; 1.0, 1.7 and 3.0 meters).

Table 2 Soil resistivity measured in the test bed

Areas	Area 1	Area 2	Area 3	Average
Soil Resistivity, kΩ·cm	22.0	29.5	26.0	25.8

on the test bed, and polyken coated carbon steel pipes were buried at 1, 1.7, and 3-meter depth, and each 6 meter-length pipes were electrically connected. Fig. 1b depicts the top view on the test bed. The anodes were buried at vertical and parallel directions to the pipeline. Cathodic protection condition was also real-time monitored. Current interrupter was also installed to measure the on-off potential of protected pipes. Buried reference electrode was copper-copper sulfate electrode (CSE, $Cu/CuSO_4$). In every pipe, coating flaws were intentionally formed from 1 to several tens square centimeters. Table 1 summarize the information of buried pipes.

2.2 Detection of coating flaw

Coating flaws were surveyed by DCVG method (MC Miller, GX Voltmeter / GPS Receiver) using two $Cu/CuSO_4$ reference electrodes. Applied voltage was controlled and the anodes vertical or parallel to pipeline were used. This work defined that the flaw was detected when the non-polarity location by DCVG method was within ± 1meter error range to the location of intentional flaw.

2.3 Calculation of detection reliability of the flaws

The location of coating flaw by DCVG measurement is determined by the reversal of polarity measured along the pipeline buried in the soil. However, numbers of the signal of the reversal of polarity may be more and less than the number of real flaws, and thus detection reliability should be calculated carefully because of inevitable error. Therefore, in this work, detection reliability was calculated according to the following equation. In the equa-

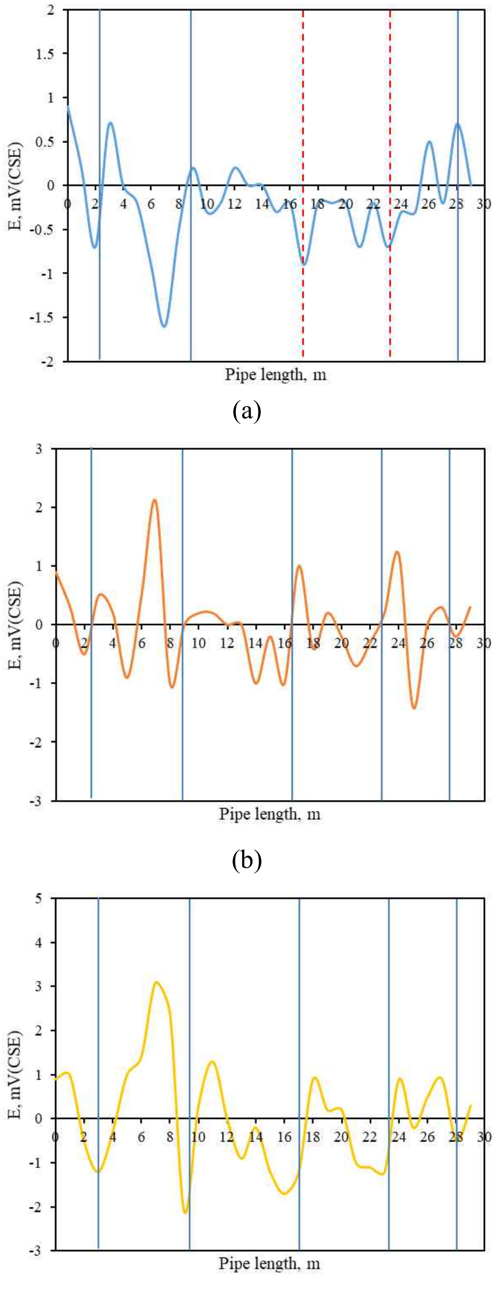


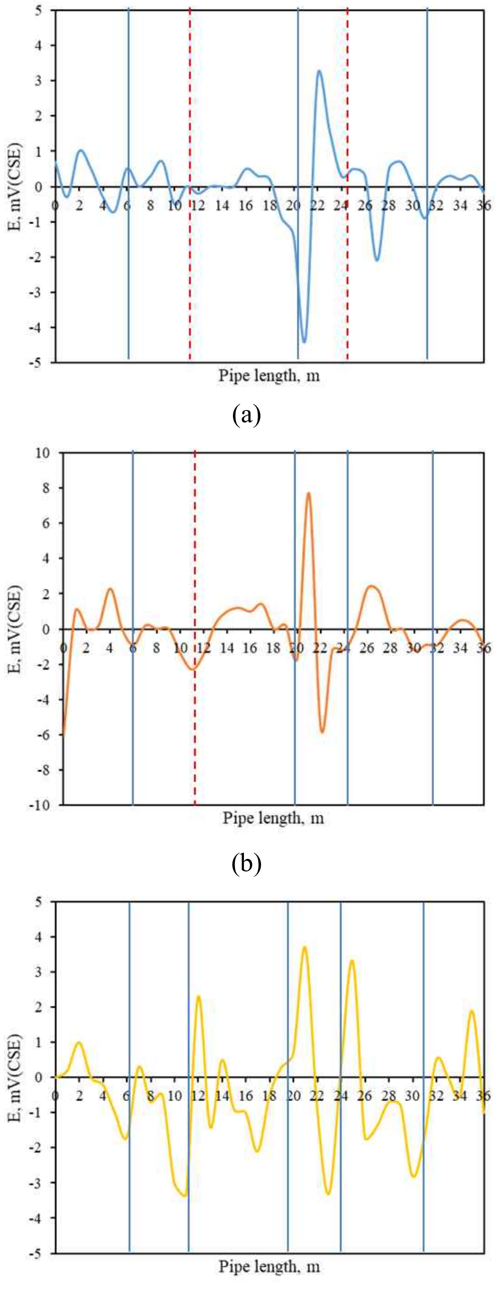
Fig. 3 Effect of applied voltage on the flaw detection of CS pipes with 1.0 meter - buried depth using the anode #2 vertical to the pipes (blue line : flaw detected, red dot line : detection failed); (a) 3 V, (b) 5 V, and (c) 7 V.

tion, detected signals imply the signals number correspond to real flaw;

$$\text{Detection reliability, \%} = \text{Detected signals} \times 2 \,/\, [\text{Real flaw number} + \text{Flaw signal number}]$$

3. Results and Discussion

Cathodic protection system was installed to monitor and control the corrosion and protection status. Fig. 2 shows the monitoring result on open circuit potential (OCP) and protection potential (CP-on) by cathodic protection for polyken coated carbon steel pipe (buried depth; 1.0, 1.7

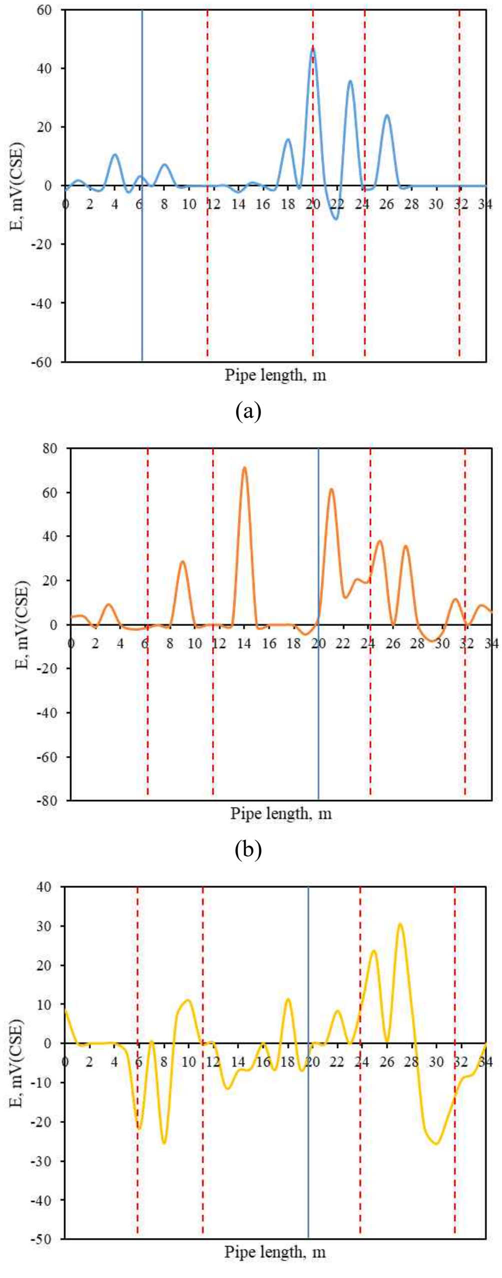


(a)

(b)

(c)

Fig. 4 Effect of applied voltage on the flaw detection of CS pipes with 1.7 meter - buried depth using the anode #2 vertical to the pipes (blue line : flaw detected, red dot line : detection failed); (a) 3 V, (b) 5 V, and (c) 7 V.



(a)

(b)

(c)

Fig. 5 Effect of applied voltage on the flaw detection of CS pipes with 1.7 meter - buried depth using the anode #3 parallel to the pipes (blue line : flaw detected, red dot line : detection failed); (a) 3 V, (b) 5 V, and (c) 7 V.

and 3.0 meters) buried in the test bed. 3 kinds of pipes revealed relatively constant OCP and protection potentials were controlled under the protection criteria (- 850 mV(CSE)). Table 2 summarized the soil resistivity measured in the test bed. The soil resistivity of test bed was measured three times and the average soil resistivity is 25.8 kΩ·cm.

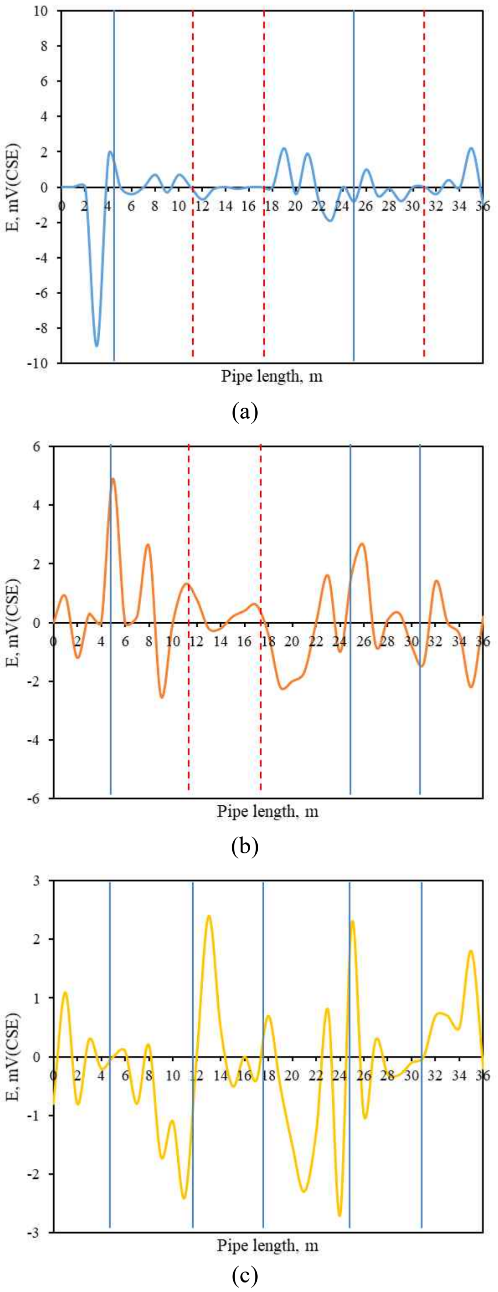


Fig. 6 Effect of applied voltage on the flaw detection of CS pipes with 3.0 meter - buried depth using the anode #2 vertical to the pipes (blue line : flaw detected, red dot line : detection failed); (a) 3 V, (b) 5 V, and (c) 7 V.

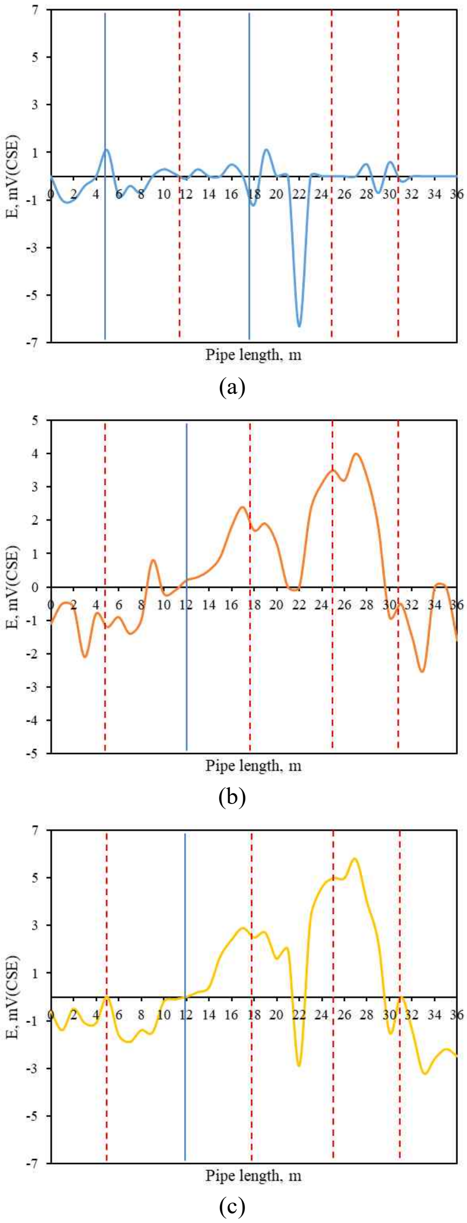
Fig. 3 shows the effect of applied voltage on the flaw detection of CS pipes with 1.0 meter - buried depth using the anode #2 vertical to the pipes. In the figures, blue line means the flaw was detected and red dot line the detection was failed. We defined that the flaw was detected when the non-polarity location by DCVG method was within ± 1meter error range to the location of intentional flaw. In the case of the applied voltage of 3 V, 3 flaws were detected among 5 flaw signals. In the case of the applied voltage of 5 V, 5 flaws were detected among 8 flaw signals. In the case of the applied voltage of 7 V, 5 flaws were detected among 6 flaw signals.

Fig. 4 reveals the effect of applied voltage on the flaw detection of CS pipes with 1.7 meter - buried depth using the anode #2 vertical to the pipes. In the case of the applied voltage of 3 V, 3 flaws were detected among 6 flaw signals. In the case of the applied voltage of 5 V, 4 flaws were detected among 6 flaw signals. In the case of the applied voltage of 7 V, 5 flaws were detected among 7 flaw signals. However, if the location of the anode was parallel to the pipeline, detection reliability was changed. Fig. 5 depicts the effect of applied voltage on the flaw detection of CS pipes with 1.7 meter - buried depth using the anode #3 parallel to the pipes. Fig. 6 shows the effect of applied voltage on the flaw detection of CS pipes with 3.0 meter - buried depth using the anode #2 vertical to the pipes. Fig. 7 reveals the effect of applied voltage on the flaw detection of CS pipes with 3.0 meter - buried depth using the anode #3 parallel to the pipes. In the case of the applied voltage of 3 V, 2 flaws were detected among 9 flaw signals. In the case of the applied voltage of 5 V, 1 flaw was detected among 2 flaw signals. In the case of the applied voltage of 7 V, 1 flaw was detected among 2 flaw signals. Table 3 summarizes the flaw detection reliability for the buried pipes with the different depths and the applied voltages. In summary, increasing the applied voltage to detect the flaws buried in the soil with the resistivity of *ca.* 25.8 kΩ·cm, detection reliability was also increased, regardless of buried depth. However, the vertical location of anode to the pipeline was very effective to detect the flaws of buried pipe, but the parallel location of anode to the pipeline was extremely non-effective.

Fig. 8 shows the relationship between buried depths and detection reliability with different applied voltage using the anode vertical to the pipes. This figure was calculated and plotted from Table 3. As shown in figure, increasing the buried depth of pipes, the detection reliability was reduced regardless of the applied voltage. This behaviour may be induced by the decreased current distribution by increasing the buried depth of pipes. Therefore, in order to get a high detection reliability, a high applied voltage

Table 3 Summary on the flaw detection reliability for the buried pipes with the different depths and the applied voltages

Detection condition		Reliability, %		
Anode position	Buried depth, m	3 V	5 V	7 V
Anode vertical to the pipes	1.0	60.0	76.9	90.9
	1.7	54.5	72.7	83.3
	3.0	36.4	50.0	76.9
Anode parallel to the pipes	1.7	18.2	20.0	25.0
	3.0	28.6	28.6	28.6



(a)

(b)

(c)

Fig. 7 Effect of applied voltage on the flaw detection of CS pipes with 3.0 meter - buried depth using the anode #3 parallel to the pipes (blue line : flaw detected, red dot line : detection failed); (a) 3 V, (b) 5 V, and (c) 7 V.

is needed.

Fig. 9 reveals the relationship between detection potential and detection reliability with different buried depths using the anode vertical to the pipes. As shown in figure, increasing the detection potential to the negative, the de-

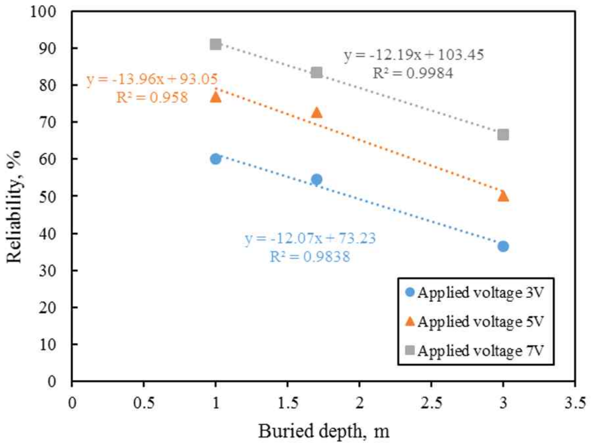


Fig. 8 Relationship between buried depths and detection reliability with different applied voltage using the anode vertical to the pipes.

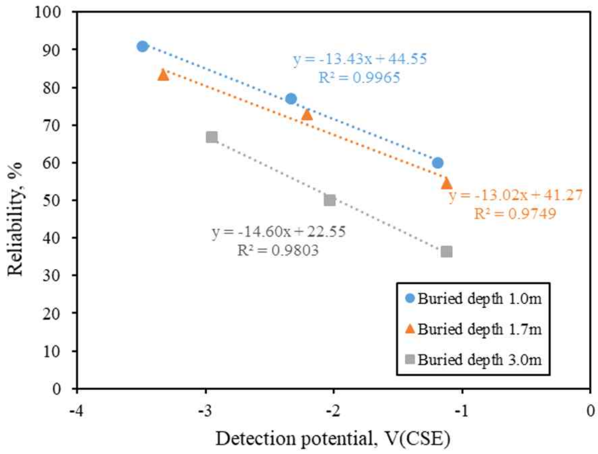


Fig. 9 Relationship between detection potential and detection reliability with different buried depths using the anode vertical to the pipes.

Table 4 Summary on the detection potential for the buried pipes at each applied voltage with the different depths

Detection condition		Detection Potential, V(CSE)		
Anode position	Buried depth, m	3 V	5 V	7 V
Anode vertical to the pipes	1.0	-1.19	-2.33	-3.49
	1.7	-1.12	-2.21	-3.33
	3.0	-1.12	-2.03	-2.95
Anode parallel to the pipes	1.7	-3.48	-5.55	-7.01
	3.0	-3.32	-5.03	-6.75

*CSE (Copper-Copper Sulfate Electrode)

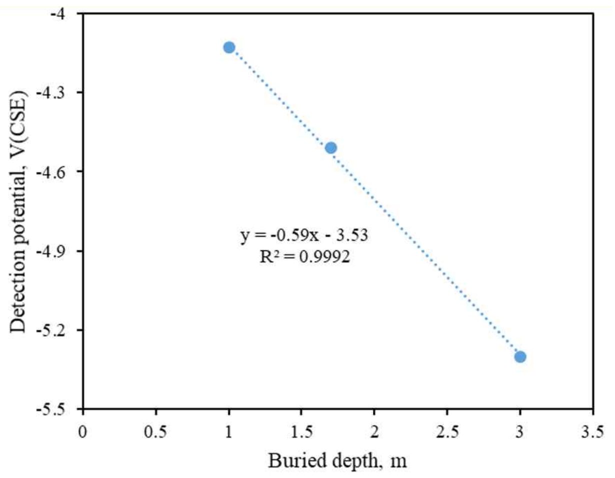


Fig. 10 Relationship between buried depth and detection potential to get 100 % detection reliability for the pipes buried in soil resistance of 25.8 kΩ·cm.

tection reliability was improved regardless of the buried depth of pipes. This behaviour may be induced by the increased current distribution by increasing the applied voltage to pipes. Therefore, in order to get a high detection reliability, a lower detection potential is needed whenever the pipes are deeper buried. However, the applied voltage to detect the coating flaws is dependent upon the amount of buried pipes and soil condition etc. Therefore, in order to improve the detection reliability, another criteria is needed. As shown in Table 4, we measured the detection potential when the voltage applied to the buried pipe during the coating survey.

From Fig. 9 and Table 4, Fig. 10 was replotted. Fig. 10 depicts the relationship between buried depth and detection potential to get the 100 % detection reliability for the pipes buried in the soil showing the resistance of 25.8 kΩ·cm. The anode shall be vertically installed to the pipes. Using Fig. 10, the needed detection potential to get a desire detection reliability can be calculated. If the pipes were buried at 4.0 meter, the lower detection potential than -5.89 V(CSE) was calculated to get 100 % detection reliability using the below equation;

$$\text{Detection potential, V(CSE)} = -0.59 \times [\text{buried depth, meter}] - 3.53$$

4. Conclusions

This work focused on the effect of survey conditions on the reliability of coating flaw detection of buried pipes in soils. The effects of applied voltage and anode location on the detection reliability of coating flaw of buried pipe in soil with the resistivity of *ca.* 25.8 kΩ·cm were discussed and concluded as follows;

1) When the applied voltage increased(detection potential decreased) to detect the flaws buried in the soil, detection reliability was also increased, regardless of buried depth. When the buried depth of pipes was deeper, the detection reliability was reduced regardless of the applied voltage. However, the vertical location of anode to the pipeline was very effective to detect the flaws of buried pipe, but the parallel location of anode to the pipeline was extremely non-effective. This behaviour may be induced by the variation of current distribution by the applied voltage and buried depth

2) The applied voltage to detect the coating flaws is dependent upon the amount of buried pipes and soil condition etc. Therefore, in order to improve the detection reliability, another criteria is needed. The needed detection potential to get a desire detection reliability can be calculated to get 100 % detection reliability using the below equation ;

$$\text{Detection potential, V(CSE)} = -0.59 \times [\text{buried depth, meter}] - 3.53$$

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