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Improvement of the Reliability of Pipelines Buried in Soil through Real-time Monitoring and Control for Cathodic Protection and Coating Defect Detection

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Buried pipelines face corrosion risks during long-term operation in soil environments, primarily due to coating defects or degradation of cathodic protection performance. To mitigate these issues, it is crucial to accurately assess the condition of cathodic protection and promptly identify any coating defects. This study investigated the cathodic protection status at domestic power plant sites and established a mock-up facility for real-time assessments of cathodic protection and coating defect detection. This was achieved using on-off potential measurements, Close Interval Potential Survey (CIPS), and Direct Current Voltage Gradient (DCVG) techniques. The findings revealed that the cathodic protection condition at existing sites was locally inadequate. In contrast, the mock-up facility allowed for continuous monitoring of on-off potential variations, and real-time CIPS and DCVG measurements effectively identified potential changes and signal reversals at the sites of intentionally introduced coating defects, aligning closely with their actual locations. These results demonstrate that implementing real-time monitoring and defect detection systems for buried pipelines in soil can significantly improve the reliability of cathodic protection management.

Keywords: *Buried pipe, Cathodic protection, CIPS, DCVG, Real-time defect detection*

1. Introduction

The corrosion behavior of materials is inherently highly sensitive to the characteristics of the operating environment. Corrosion in soil environments occurs according to the same fundamental principles as corrosion in aqueous solutions. The main difference lies in the mobility of corrosive species, which is relatively high in aqueous environments but limited in soil. In addition, certain environmental factors that induce corrosion, such as the activation of stray currents in the soil and the presence of anaerobic bacteria, differ to some extent between the two environments [1,2].

According to the first survey conducted by the National Bureau of Standards (NBS) [3], the economic loss due to corrosion in the United States was estimated to be approximately 70 billion USD, corresponding to about 4% of the gross national product. More recent surveys have reported that the direct loss caused by corrosion amounts to 279 billion USD, accounting for about 3.2% of the GDP [4]. When including indirect losses such as social costs, the overall loss is conservatively estimated to reach nearly 6% of GDP. In Korea, a relatively recent survey conducted in 2009 by the Korean Corrosion Science and Protection Society reported corrosion losses equivalent to 2.9% of GDP, indicating that corrosion damage cannot be overlooked [5]. In the case of buried pipelines in soil, corrosion not only leads to costs associated with equipment repair, replacement, and labor, but also raises more critical concerns regarding public

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hygiene and health related to water quality. Moreover, corrosion-induced failures of underground storage tanks containing hazardous materials or high-pressure gas pipelines can result in extremely serious safety problems.

Most structures used in soil environments are made of steel. Since corrosion occurs when steel comes into contact with moisture, various types of coating materials are applied to prevent direct contact between steel structures and moisture in the soil [6,7]. However, these coatings may develop defects either during construction or over time in service [8,9]. When such defects are present, corrosion can initiate at these sites, and therefore separate management is required to control them.

Therefore, cathodic protection is often applied in soil environments to prevent corrosion at coating and paint defect sites [10,11]. In some cases, when structures are located in confined areas of relatively dry soil, the corrosion rate is comparatively slow, and cathodic protection may not be implemented. However, from a long-term service perspective, combining cathodic protection with coating systems is more economical. when technically reliable and economically feasible protection is required, it is necessary to consider the simultaneous application of coating technology and cathodic protection. The combined use of these protection methods has been proven to provide higher technical reliability and greater economic efficiency compared to either leaving the structures unprotected or applying a single method alone. Since then, this combined approach has been routinely applied worldwide in the prevention of soil corrosion of buried pipelines and similar structures.

Cathodic protection is a technique that suppresses the anodic reaction responsible for corrosion by artificially controlling the potential of a structure. In other words, corrosion occurs when the natural potential of a structure (measured against a copper–copper sulfate electrode, CSE) is above a certain level, and by applying an external current to lower this potential, the structure is polarized cathodically, thereby suppressing the anodic corrosion reaction. Previous observations have shown that when the instant off-potential of underground steel structures decreases to below −850 mV(CSE), corrosion is effectively suppressed [12–14].

Cathodic protection is generally applied in combination with protective coatings. The primary protection effect is provided by the coating layer. However, coatings inevitably contain defects due to inherent imperfections, mechanical damage during construction, or degradation over time [8,10,11]. Cathodic protection serves as a complementary technique to prevent corrosion at these coating defects. If cathodic protection were applied alone to underground steel structures without coatings, the required protection current would be excessively large due to the wide exposed surface area, making it economically impractical. Therefore, the combined use of coatings and cathodic protection is not only more economical but also essential to achieving complete protection.

Therefore, for the effective management of buried pipelines, it is important not only to apply coatings in combination with cathodic protection but also to employ inspection techniques that can promptly identify coating damage. Various coating defects and anomalies, such as degradation, disbondment, delamination, blistering, or improper application, can lead to localized external corrosion of buried pipelines, including pitting, crevice corrosion, intergranular attack, and cracking [15–23]. To prevent such problems, it is essential to detect and repair coating damage at an early stage. For this purpose, indirect evaluation methods for external corrosion of pipelines are commonly employed, including Close Interval Potential Survey for determining cathodic protection conditions [24] and Direct Current Voltage Gradient surveys for locating coating defects [25]. In addition, other techniques such as Area Potential and Earth Current (APEC), the Pearson Survey, and Alternating Current Voltage Gradient (ACVG) are also utilized [26–28].

In the case of domestic power facilities, it has been reported that more than 30 ~ 40 km of pipelines are buried in soil, and the underground structures are highly complex, with multiple pipelines installed in parallel, making the application of cathodic protection particularly challenging. Moreover, since most of these pipelines have been buried and in operation for several decades, the cathodic protection systems themselves are often aged and deteriorated.

Moreover, with the recent commercialization of Remote Monitoring Units (RMUs) and IoT-based fixed monitoring systems, it has become possible to collect and control the voltage and current at limited points such as rectifiers and test boxes (T/B) in real time. However, while this method is effective for checking the status at specific locations, it cannot continuously monitor potential changes across the entire pipeline section, making it difficult to directly pinpoint the location of coating defects.

Therefore, this study analyzed the current state of cathodic protection management for buried pipelines at domestic power plants and constructed two mock-up facilities to apply a real-time monitoring and coating defect detection and control system. This aimed to enhance the reliability of corrosion management and operational efficiency for buried pipelines.

2. Experimental methods

2.1 Potential measurement of cathodic protection in a power plant

Fig. 1 illustrates the schematic layout of three pipeline sections selected to evaluate the cathodic protection condition of buried pipelines at domestic power plants. The black solid lines represent the pipeline routes, and the measurement distance at each site ranged from 50 to 70 m. A cathodic protection rectifier was installed at each location, while the red circles indicate the positions of buried anodes. T/B denotes the test box, where a $Cu/CuSO_4$ reference electrode was embedded for potential inspection. Re-1, Re-2, and Re-3 refer to newly buried $Cu/CuSO_4$ reference electrodes installed for real-time monitoring of cathodic protection potential, with the measured potentials continuously recorded using a data logger.

2.2 Mock-up facility establishment for cathodic protection and defect detection

Fig. 2 presents the layout and actual photographs of the mock-up test facilities installed at Gyeongkuk National University and a domestic power plant. Fig. 2a shows a schematic of the Gyeongkuk National University facility, where three carbon steel pipelines, each 30 m in length, were buried at depths of 2.3 m, 2.5 m, and 3.0 m from the ground surface. Intentional coating defects (holidays) were introduced on the outer surface of each pipeline. To monitor the cathodic protection condition, a $Cu/CuSO_4$ reference electrode (Re-0) was buried near the pipelines, and two Ti/MMO anodes (anode 1 and anode 2) were placed parallel to the pipelines. In addition, a total of 30

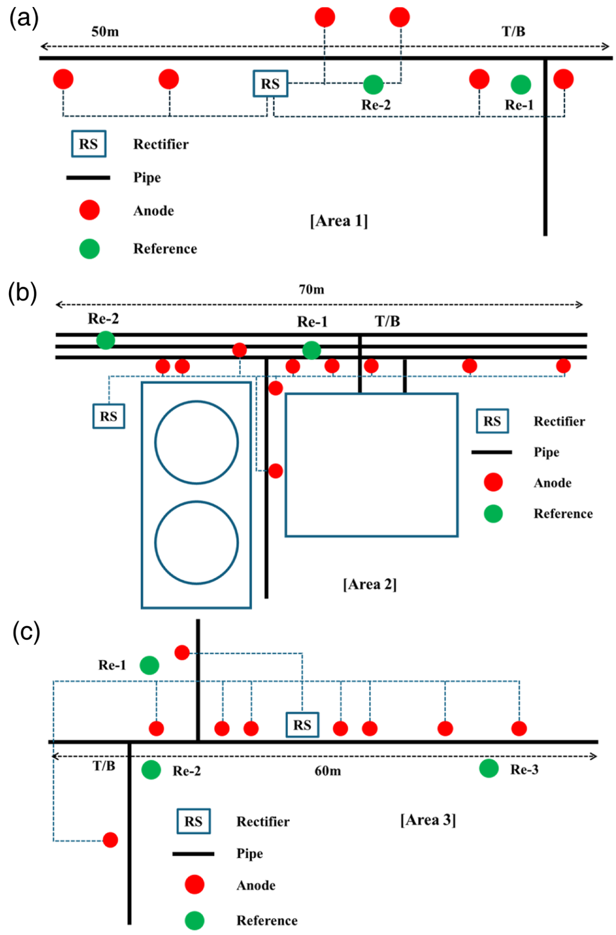

Fig. 1. Schematic diagram of buried pipeline (−), anode (🔴), rectifier, and test box(T/B) and monitoring electrode (🟢) in domestic power plant; (a) Area 1, (b) Area 2, (c) Area 3

$Cu/CuSO_4$ reference electrodes (Re-1 to Re-30) were installed at 1 m intervals along the ground surface to measure potential variations caused by the coating defects. Temperature, humidity, and conductivity sensors were also installed to monitor the soil environment.

Fig. 2b shows a schematic of the mock-up facility installed at a domestic power plant. Two pipeline sections, each 6 m in length, were connected and buried, and a $Cu/CuSO_4$ reference electrode (Re-0) was embedded near the pipeline to monitor the cathodic protection condition. A total of 15 $Cu/CuSO_4$ reference electrodes were installed on the ground surface at intervals of 1, 2, and 3 m to enable defect detection of the buried pipelines. Fig. 2c shows actual photographs of carbon steel pipes and cast iron pipes buried at a domestic power plant, with artificial coating defects (holidays) of 5 cm^2 formed on the pipe outer surface. These defects were applied to simulate

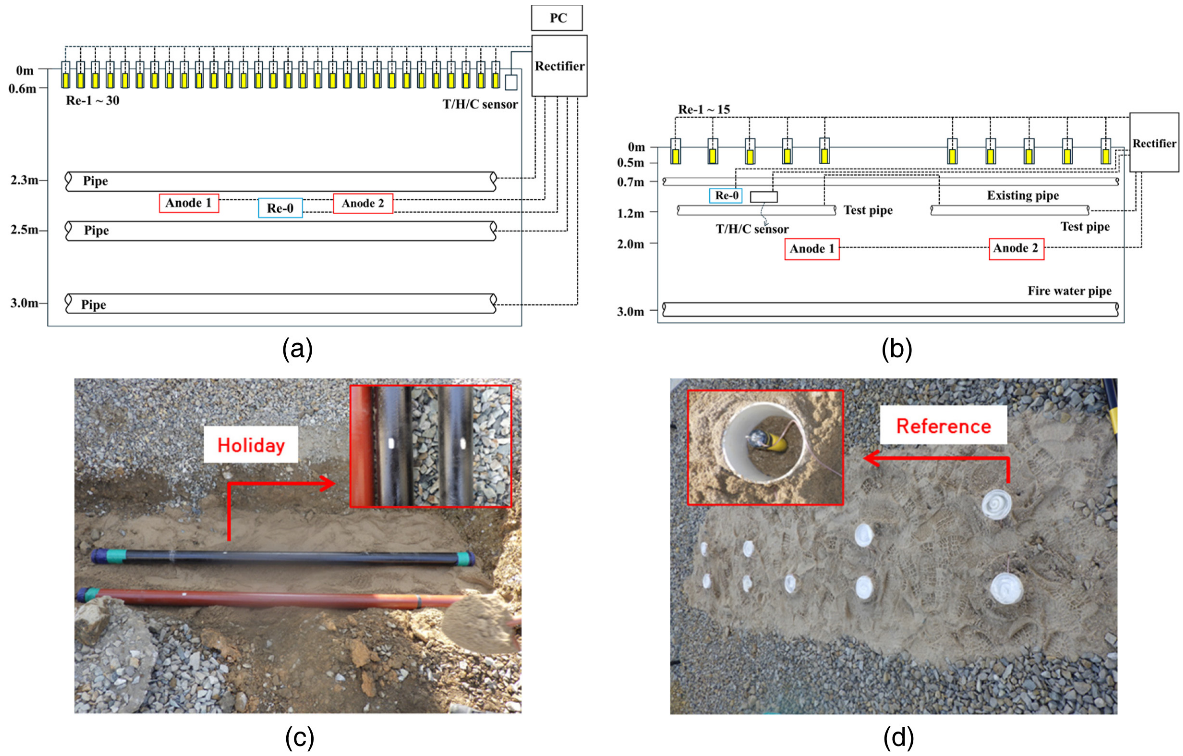

Fig. 2. (a) Mock-up diagram in Gyeongkuk National University, (b) mock-up diagram in domestic power plant, (c) photo of buried pipe, (d) photo of monitoring electrodes

actual coating damage that could occur under cathodic protection conditions. According to a previous study [29], field surveys of buried pipelines in power plants reported that coating defects larger than 5 cm^2 showed an inspection success rate of approximately 62.5% using indirect inspection methods such as CIPS and DCVG. Therefore, this study selected 5 cm^2 as the minimum standard defect size for verifying the inspection performance of the proposed system. Fig. 2d shows a photograph of the Cu/$CuSO_4$ reference electrodes installed on the ground surface.

2.3 On–Off potential measurement

The on-off potential measurement is a fundamental method for evaluating the cathodic protection condition of buried pipelines. Fig. 3 illustrates the measurement principle. The on-potential is the potential measured between the pipeline and the soil while the rectifier is applying cathodic protection current, and it includes the IR drop caused by soil resistance. To correct this effect, the instant off-potential is measured by momentarily interrupting the rectifier. For each mock-up pipeline, a current interrupter was used to measure both the on-potential and the instant-off potential. The off-potential is indicated by the red dot in Fig. 3.

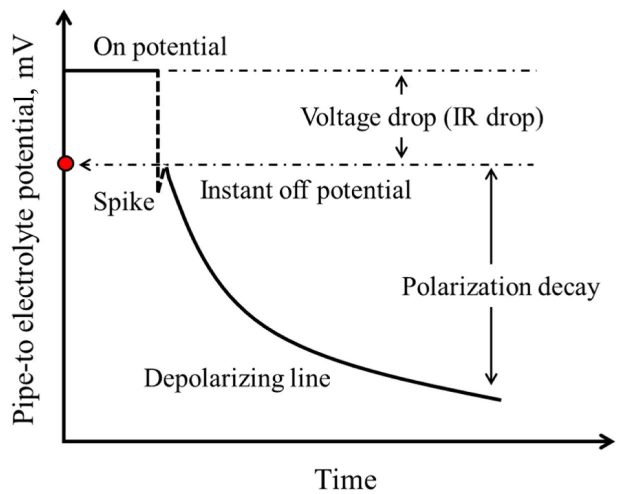

Fig. 3. Principle of on–off potential measurement showing IR drop and polarization decay

2.4 Real-time CIPS and DCVG survey for buried pipelines

CIPS and DCVG measurements are representative electrical survey techniques that use direct current sources

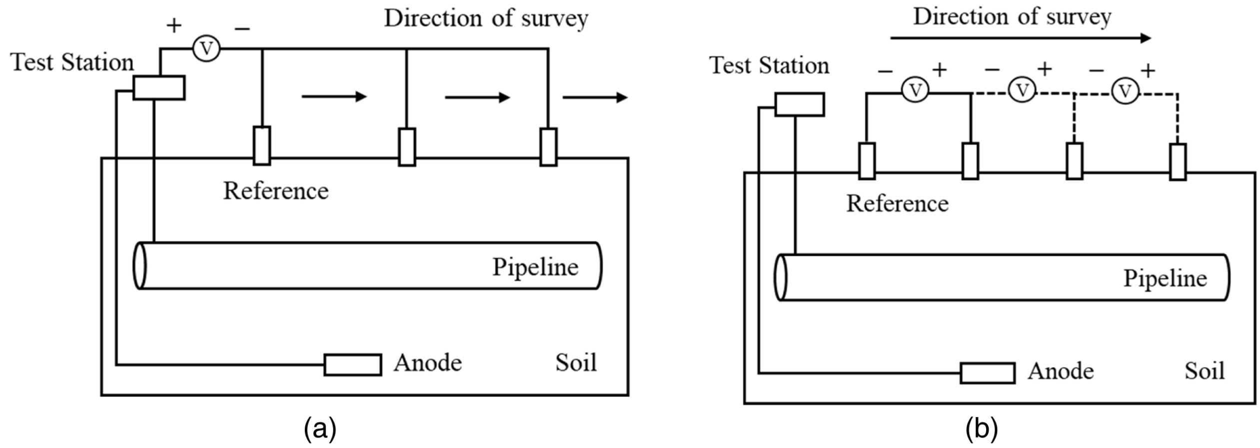

Fig. 4. Schematic illustration of measurement principles: (a) Close Interval Potential Survey, (b) Direct Current Voltage Gradient

to indirectly detect coating defects in buried pipelines. Fig. 4 schematically illustrates the measurement principles of these two methods. CIPS involves moving a reference electrode at regular intervals along the pipeline to continuously measure the pipe-to-soil potential (Fig. 4a). This method allows the potential distribution of the pipeline to be evaluated, with distinct local potential variations observed at defect sites. DCVG, on the other hand, employs two detection electrodes placed on the ground surface, which are moved along the pipeline route while measuring the potential difference between them (Fig. 4b). At coating defect sites, current flow becomes concentrated, producing a significant potential gradient signal, and the signal polarity reverses at the defect location. In this study, the principles shown in Fig. 4 were applied in real time to measure potential and potential differences, and these data were subsequently used to calculate the detection rate [30] and in this work, defect detection was confirmed when the defect signal was detected within an error range of ± 2 m from the actual location of the defect [31-33].

4. Results and Discussion

Fig. 5 shows the results of on-potential measurements for buried pipelines in three areas of a domestic power plant. In Area 1 (Fig. 5a), the measured potentials ranged from −1.9 V(CSE) to −0.70 V(CSE). A large variation in potential values was observed across sections, and at certain points, values as low as −0.72 V(CSE) were

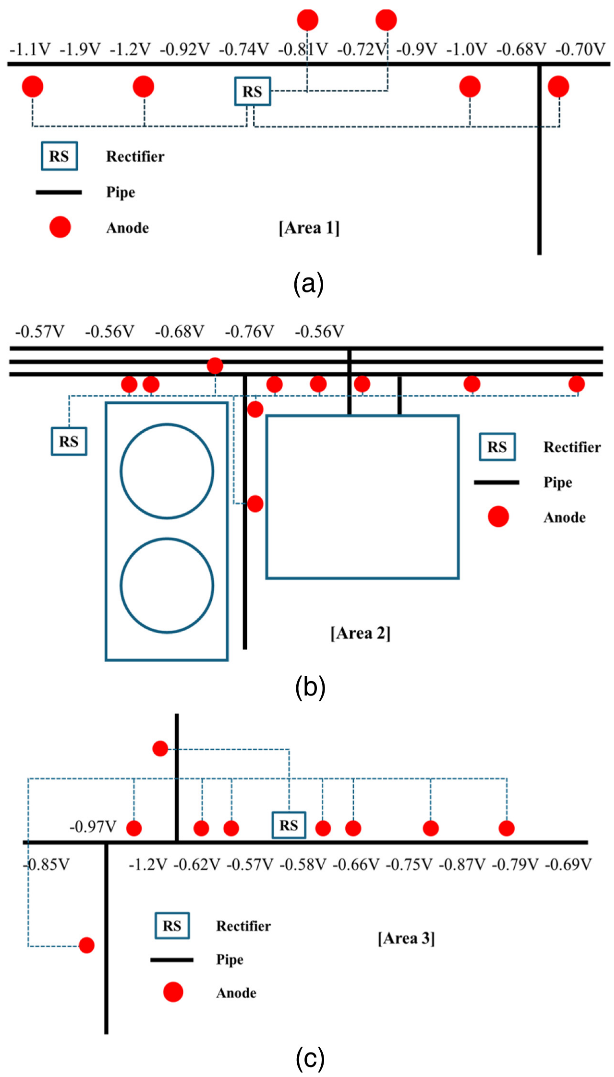

Fig. 5. Pipe-to-soil potential measured in Fig. 1's power plant (the potentials represent the pipe-to-soil potential measured at its location; (a) Area 1, (b) Area 2, (c) Area 3

recorded, which did not meet the protection criterion of −0.85 V(CSE) (based on off-potential) [12-14], even though these were on-potential measurements. This result is attributed to non-uniform current distribution and local variations in soil resistivity, which prevented consistent protection across the section. In Area 2 (Fig. 5b), the measured potentials ranged from −0.76 V(CSE) to −0.56 V(CSE), with all values below the protection criterion of −0.85 V(CSE). In Area 3 (Fig. 5c), the potentials ranged from −1.20 V(CSE) to −0.69 V(CSE). While most sections maintained values above −0.97 V(CSE), certain locations showed values as low as −0.69 V(CSE). These results indicate that the cathodic protection potentials were not consistently maintained across the sections, which can be attributed to local coating damage or variations in soil conditions. Taken together, the measurements from the three areas indicate that the on-potentials obtained using CSE electrodes at the actual power plant site exhibited large variations across sections. This demonstrates that on-potential measurements alone are insufficient to accurately assess the cathodic protection condition, as they only provide instantaneous values at the time of measurement and give no information about potential changes occurring during the operation period of the facility.

Fig. 6 shows the real-time monitoring results of pipe-to-soil potentials measured using reference electrodes installed in the three areas (Area 1, Area 2, Area 3) presented in Fig. 1 at a domestic power plant. Fig. 6a presents the pipe-to-soil potentials measured in Area 1. Re-1 gradually decreased over time, reaching approximately −1.3 V(CSE), after which it maintained a stable value. In contrast, Re-2 initially increased to about −0.5 V(CSE), but after 1700 h it sharply decreased to −0.9 V(CSE), followed by a subsequent increase. Fig. 6b shows the measurements in Area 2. Both Re-1 and Re-2 initially recorded potentials of approximately −1.8 V(CSE). After 100–200 h of operation, the potentials gradually increased to around −1.0 V(CSE). However, after 1400 h, the potentials decreased again to the range of −2.0 to −1.8 V(CSE), which was subsequently maintained. Fig. 6c shows the variations of on-potentials in Area 3. Re-1 started at about −0.3 V(CSE) and dropped sharply to −1.2 V(CSE) near 300 h. It then recovered to around −0.75 V(CSE) and remained stable for a long period without significant

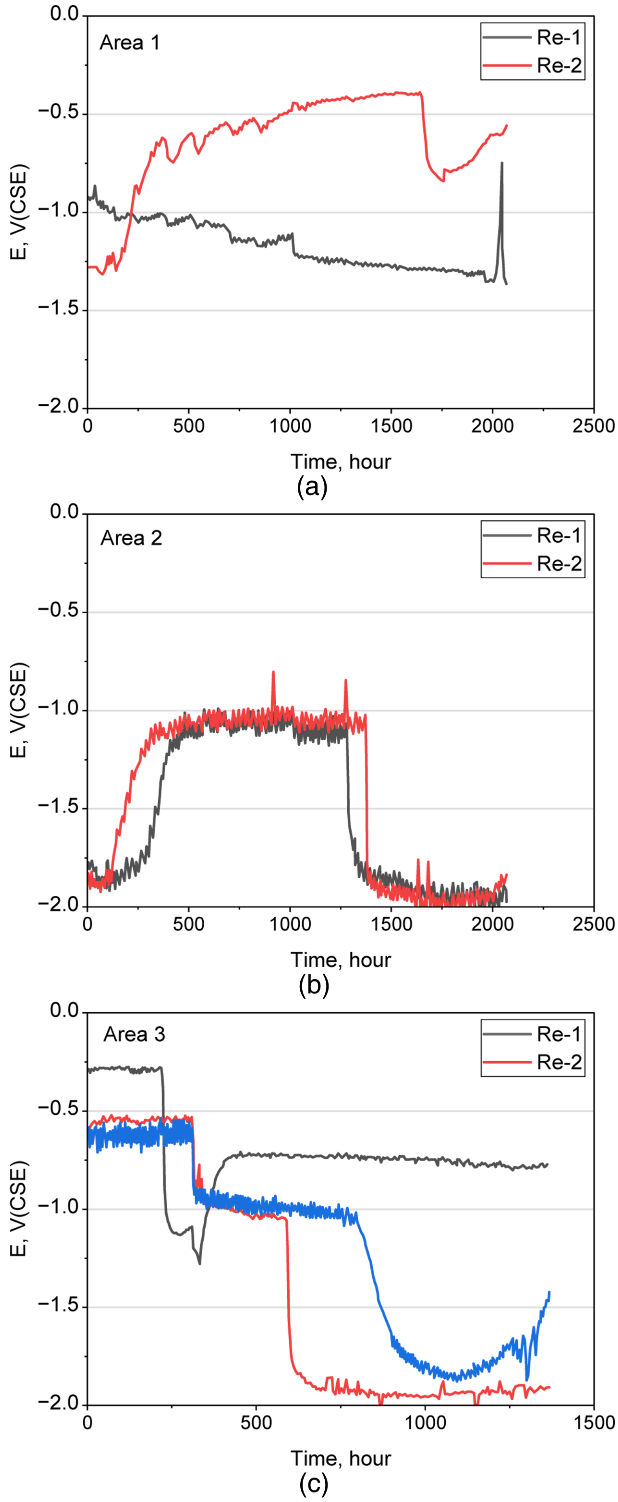

Fig. 6. Real-time monitored pipe-to-soil potentials at Fig. 1's reference electrode location; (a) Area 1, (b) Area 2, (c) Area 3

changes. Re-2 started at approximately −0.55 V(CSE) and decreased to −1.0 V(CSE) at around 300 h. It then showed a gradual decline, followed by a sharp drop near 600 h, reaching −1.9 V(CSE), which was subsequently maintained. Re-3 started at approximately −0.7 V(CSE) and decreased to −1.0 V(CSE) after 300 h. It then gradually declined further, and near 800 h it dropped sharply to −1.5 V(CSE), after which it remained at this value.

Fig. 7 shows the seasonal variations of on and off-potentials measured in real time for a pipeline buried at a depth of approximately 2.5 m in the mock-up facility installed at Gyeongkuk National University. Measurements were conducted using a copper/copper sulfate electrode buried at a depth of about 2.3 m from the ground surface, and the on and off-potentials were distinguished using a current interrupter. Fig. 7a presents the winter measurement results. The on-potential ranged from approximately −1.5 V (CSE) to −1.3 V(CSE), gradually decreasing over the entire monitoring period. The off-potential remained stable at around −1.0 V(CSE), consistently lower than the protection criterion of −0.85 V(CSE). This indicates that cathodic protection was sufficiently maintained even under the relatively low soil temperature and high resistivity conditions of winter. Fig. 7b shows the results obtained in spring. The on-potential ranged between −1.4 V(CSE) and −1.2 V(CSE), showing slightly higher values compared with those measured in winter. The off-potential was measured at an average of about −0.95 V(CSE), which was also consistently lower than the criterion of −0.85 V (CSE). As shown, the on and off-potentials measured in real time at the mock-up facility remained stable despite seasonal variations. In particular, the fact that the off-potential consistently remained below −0.85 V(CSE) throughout the entire measurement period confirms that the pipeline satisfied the cathodic protection criterion. These results demonstrate that the real-time monitoring system can be effectively utilized to evaluate the long-term stability of cathodic protection performance.

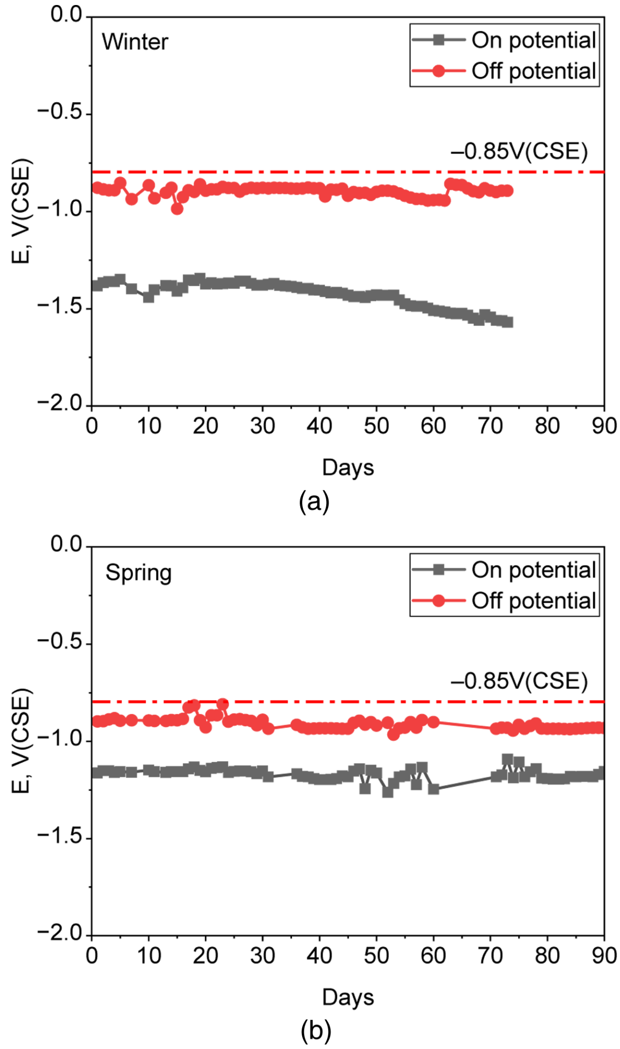

Fig. 7. Real-time monitored on-potential and off-potential of mock-up facility in Gyeongkuk National University of Fig. 8(a); (a) Winter, (b) Spring

Fig. 8 shows the DCVG results obtained using the real-time monitoring system at the mock-up facility of Gyeongkuk National University. Each pipeline was installed at different burial depths, and the DCVG signals were analyzed in relation to the intentionally created coating defect locations. In the graph, the blue dashed lines indicate points where the actual coating defect positions coincided with the signal reversal of the DCVG measurement, while the red dashed lines represent defect locations that were intentionally introduced but not detected by the DCVG measurement. Fig. 8a presents the results for the pipeline buried at a depth of 2.3 m, where DCVG signal reversals were observed at all intentionally created defects located at 3 m, 10 m, 18 m, and 24 m. The detection rate was 100%, indicating that all defects were successfully identified.

Fig. 8b presents the results for the pipeline buried at a depth of 2.5 m, where all intentionally created defects at 3 m, 15 m, and 24 m exhibited clear signal reversals. In this case as well, the detection rate was 100%, and the measured signals matched the defect locations. Fig. 8c shows the results for the pipeline buried at a depth of 3.0 m, where defects were introduced at 3 m, 9 m, 15 m, and 24 m. However, the DCVG measurement did not

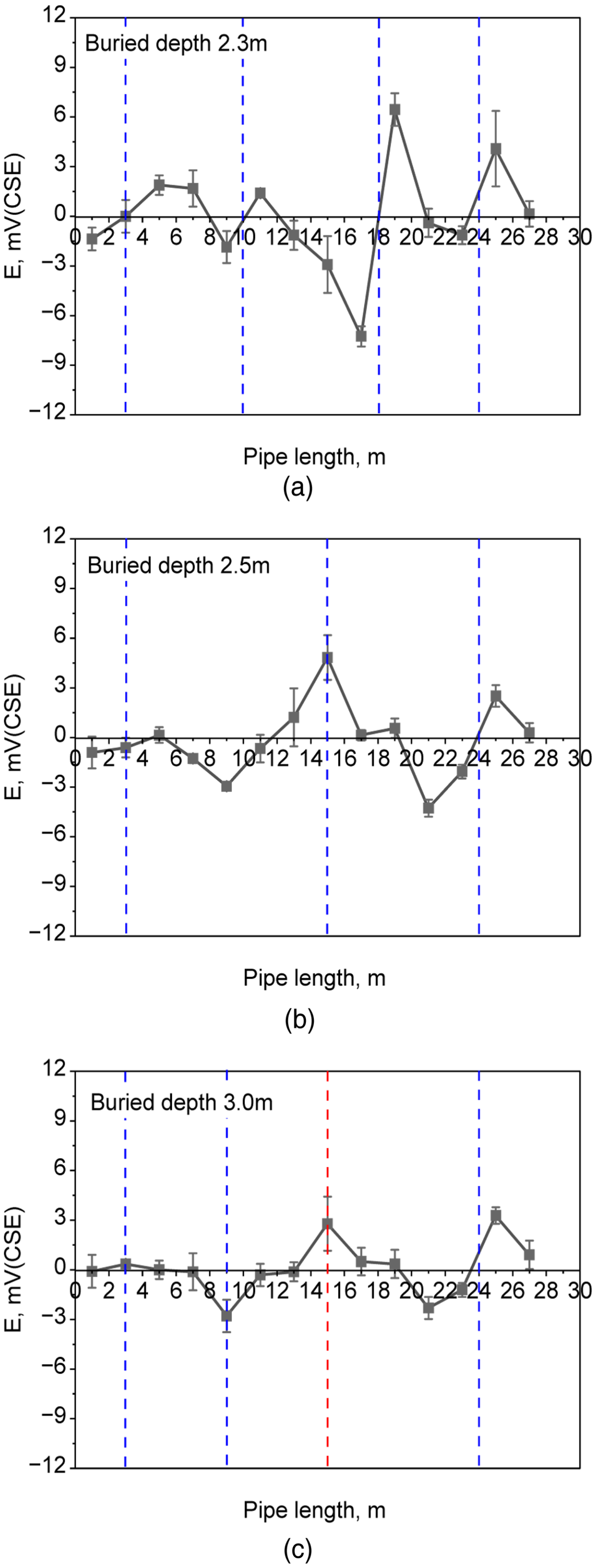

Fig. 8. Real-time monitored DCVG results of mock-up facility in Gyeongkuk National University of Fig. 8(a); (a) Buried depth 2.3 m, (b) Buried depth 2.5 m, (c) Buried depth 3.0 m

reveal a distinct signal at the 15 m defect, resulting in a reduced detection rate of 85.7%. These findings demonstrate that as burial depth increases, the defect detection signals become weaker and the detection rate decreases. This can be attributed to the attenuation of potential gradient signals with greater distance between the surface electrodes and the pipeline, as well as the influence of surrounding soil conditions and environmental factors (such as nearby pipelines), which make the measured signals less stable.

Fig. 9 presents the real-time monitoring results of the cathodic protection potentials for carbon steel and cast iron pipes in the mock-up test facility installed at a domestic power plant. The dashed line in the graphs indicates −0.85 V(CSE), which is commonly used as the

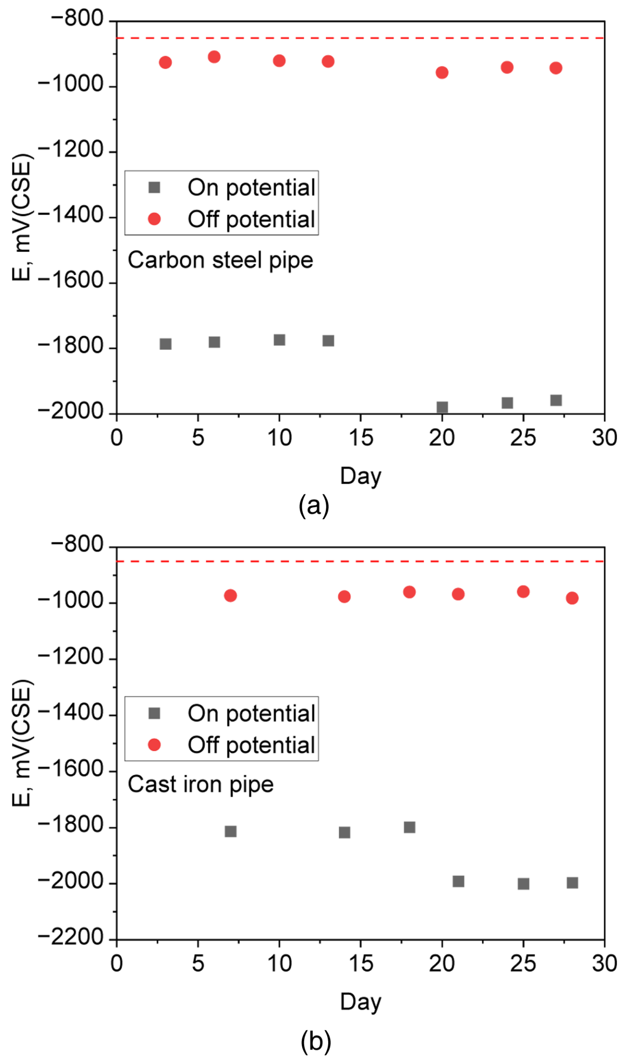

Fig. 9. Real-time monitored on-potential and off-potential of mock-up facility in domestic power plant of Fig. 8(b); (a) Carbon steel pipe, (b) Cast iron pipe

cathodic protection criterion. Fig. 9a shows the potential of the carbon steel pipe. During the initial operation, the On potential was stably maintained at around −1,800 mV(CSE). The off-potential remained near −950 mV(CSE), gradually decreasing with time. To address this, the protection voltage was increased, and after 15 days of operation, the On potential stabilized within the range of −2,000 mV(CSE) to −1,900 mV(CSE). Meanwhile, the Off potential consistently remained within −1,000 mV(CSE) to −900 mV (CSE), satisfying the protection criterion. Fig. 9b shows the potential of the cast iron pipe. Similar to the carbon steel pipe, the On potential was maintained at approximately −1,800 mV(CSE) throughout the operation period. The Off potential stabilized near −900 mV(CSE), but with slight variations over time, the protection voltage was also increased. As a result, the On potential shifted to the range of −2,000 mV(CSE) to −1,900 mV(CSE), while the Off potential stabilized between −1,000 mV(CSE) and −950 mV(CSE), thereby meeting the protection criterion. Therefore, the results in Fig. 9 confirm that both carbon steel and cast iron pipes maintained stable cathodic protection conditions during the test period, with Off potentials consistently satisfying the −0.85 V(CSE) criterion through proper adjustment of the protection voltage.

Fig. 10 shows the results of CIPS measurements performed using the real-time inspection program installed at a domestic power plant. The applied voltage was set to 4 V, and the location error of the CIPS detection results was defined as ± 2 m. Fig. 10a presents the results for the carbon steel pipe at a detection electrode–pipe distance of 1.2 m. Distinct potential variations with peaks were observed near 3 m and 13 m, corresponding to the intentional coating defect positions indicated by the blue dashed lines. Fig. 10b shows the results for the cast iron

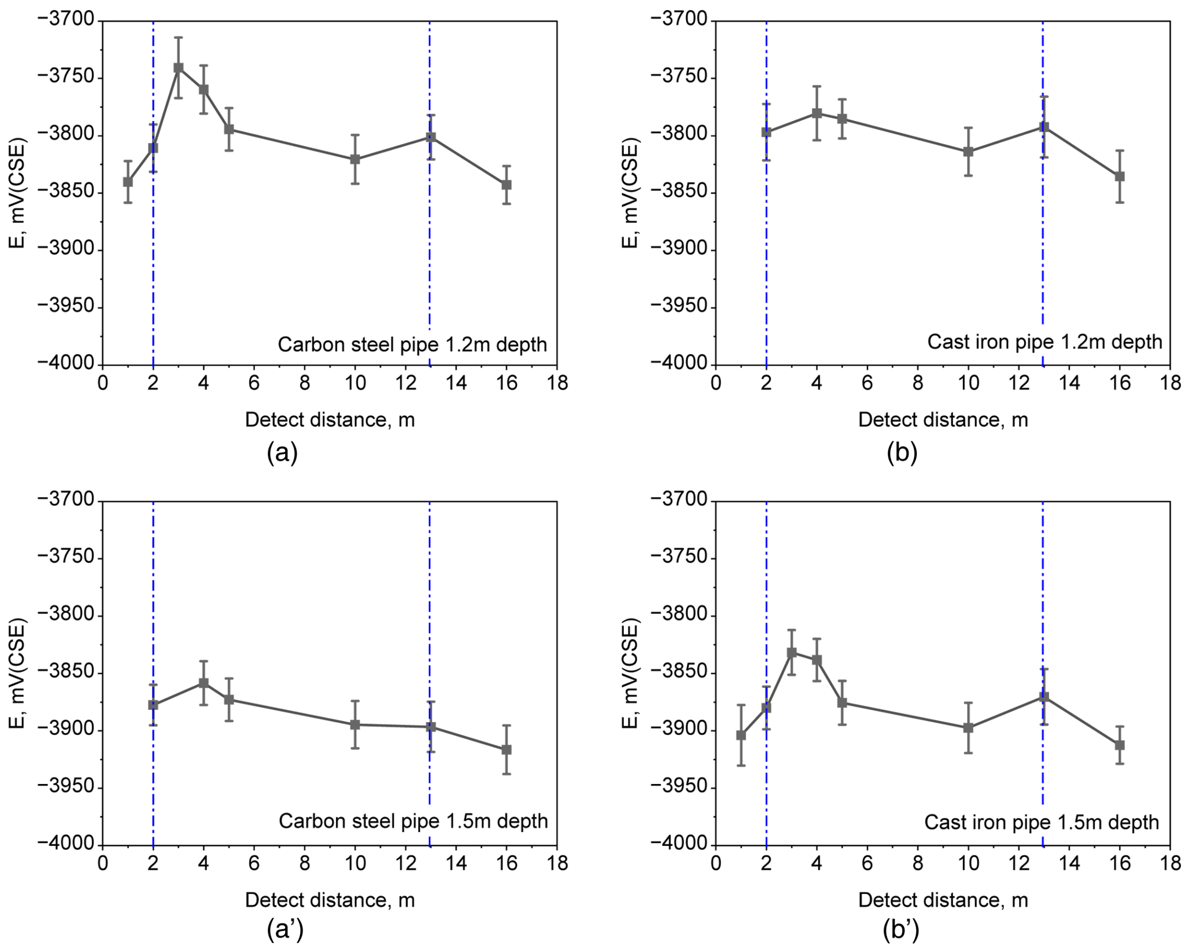

Fig. 10. Real-time CIPS results of mock-up facility in domestic power plant of Fig. 8(b); (a) Carbon steel pipe in 1.2 m depth, (b) Cast iron pipe in 1.2 m depth, (a') Carbon steel pipe in 1.5 m depth, (b') Cast iron pipe in 1.5 m depth

pipe at a detection electrode–pipe distance of 1.2 m. Potential variations indicating defects were observed at 4 m and 13 m, matching the locations of the actual intentional coating defects. Fig. 10a′ shows the results for the carbon steel pipe at a detection electrode–pipe distance of 1.5 m. Defect signals were detected at 4 m and 13 m; however, the magnitude of the potential variations was reduced compared with the 1.2 m condition. The peak positions were consistent with the blue dashed lines or appeared within the ± 2 m error range [31-33]. Fig. 10b′ shows the results for the cast iron pipe at a detection electrode–pipe distance of 1.5 m. Potential variations corresponding to defects were observed at 3 m and 13 m, and their positions were consistent with the actual intentional defects within the ± 2 m error range [31-33].

Fig. 11 presents the results of DCVG measurements performed using the real-time inspection program installed at a domestic power plant. The applied voltage was set to 4 V, and the detection error of the DCVG measurements was defined as ± 2 m. Fig. 11a shows the results for the carbon steel pipe at a detection electrode–pipe distance of 1.2 m. Distinct potential reversal signals were observed near 2 m and 14 m, coinciding with the intentional coating defect locations. The detection rate was evaluated as 100%. Fig. 11b shows the results for the cast iron pipe at a detection electrode–pipe distance of 1.2 m. Potential reversal signals were detected at 2 m and 13 m, matching the actual coating defect locations. The detection rate was evaluated as 100%. Fig. 11a′ shows the results for the carbon steel pipe at a detection electrode–pipe distance of 1.5 m. Potential reversal signals corresponding to defects were identified near 3 m and 13 m, coinciding with the intentional defect locations within the ± 2 m error range. The detection rate was evaluated as 100%. Fig. 11b′ shows the results for the cast

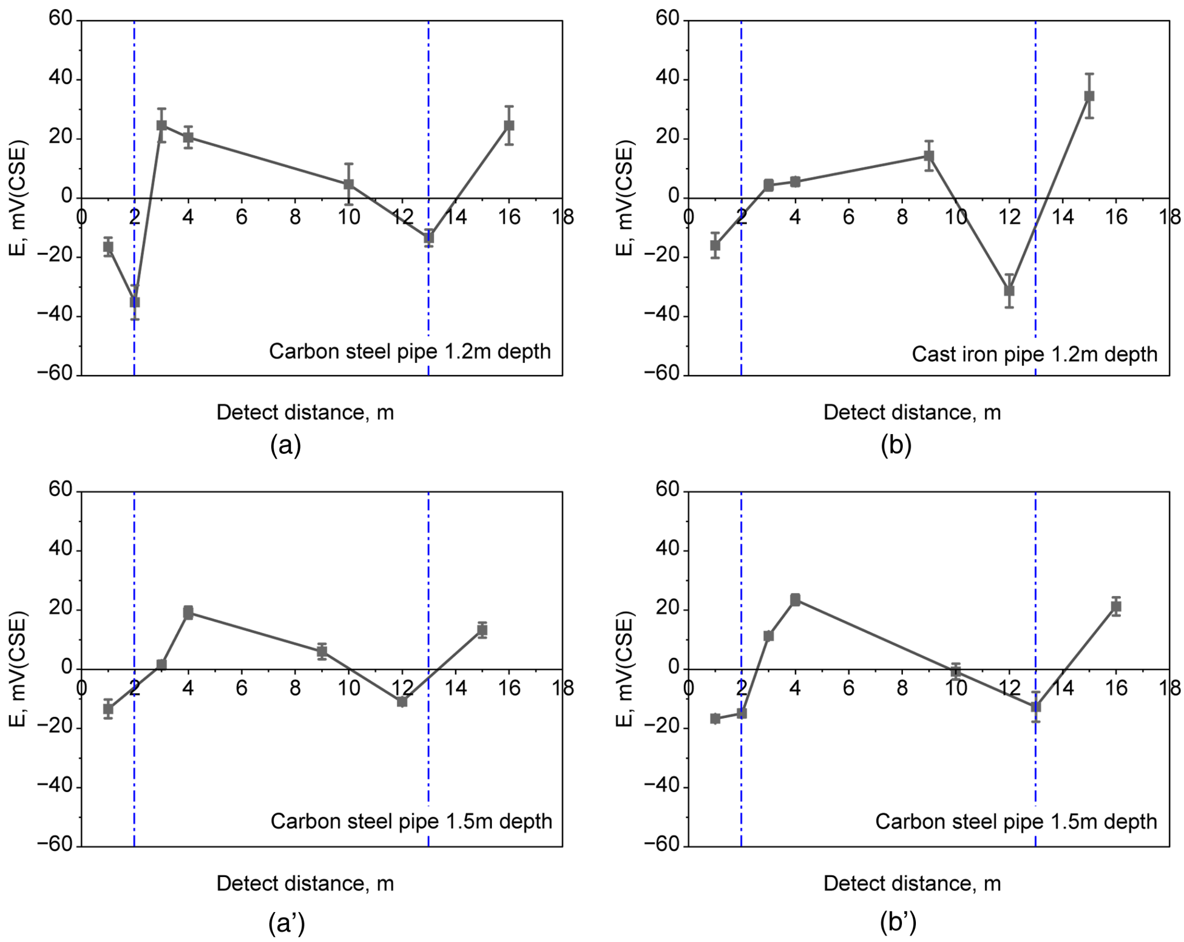

Fig. 11. Real-time DCVG results of mock-up facility in domestic power plant of Fig. 8(b); (a) Carbon steel pipe in 1.2 m depth, (b) Cast iron pipe in 1.2 m depth, (a') Carbon steel pipe in 1.5 m depth, (b') Cast iron pipe in 1.5 m depth

iron pipe at a detection electrode–pipe distance of 1.5 m. Clear potential reversal signals were observed at 3 m and 14 m, consistent with the defect locations. The detection rate was evaluated as 100%. If the electrical interference affected the detection, a detection rate could be lowered [30,33], but this did not happened in this case because the reference electrodes for defect detection were buried close to the pipelines. This configuration is effective when the pipeline handles hazardous materials that are difficult to repair or could pose serious risks in the event of a failure.

5. Conclusions

This study analyzed the cathodic protection management of buried pipelines in domestic power plants and applied real-time monitoring and inspection techniques at mock-up test facilities using On–Off potential, CIPS, and DCVG measurements. The following conclusions were obtained:

1) Monitoring of the cathodic protection conditions in existing power plants revealed that, in certain sections, the protection potentials deviated from the protection criterion and were inadequately maintained. This was mainly attributed to the limitation of conventional monitoring, which checks the potential only at T/B points during periodic inspections.

2) By installing a real-time measurement system in the mock-up facility, On and Off potentials were periodically measured and saved. This allowed cumulative cathodic protection conditions, thereby enabling more effective management of the protection system.

3) A real-time coating defect survey system was implemented, which successfully detected the vast majority of intentional coating defects, demonstrating high reliability under the tested conditions up to 2.5 m depth. These results demonstrated that the reliability of buried pipelines can be significantly improved through real-time inspection. In particular, this system is considered highly useful for pipelines that are difficult to repair or that handle hazardous materials where failures would pose serious risks.

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