Int. J. Electrochem. Sci., 15 **(2020)** 7013 – 7026, doi: 10.20964/2020.07.80

International Journal of
ELECTROCHEMICAL
SCIENCE
www.electrochemsci.org

Optimization of Cathodic Protection System for River-Crossing District Heating Pipeline using Computational Analysis: Part I. The Basic Model

Min-Sung Hong[1], *Young-Shin Jeon*[2], *Woo-Cheol Kim*[2], *Joon Cheol Jeong*[2], *Jung-Gu Kim*[1,*]

[1] School of Advanced Materials Engineering, Sungkyunkwan University, 300 Chunchun-Dong, Jangan-Gu, Suwon 440-746, South Korea;
[2] Frontier Research & Training Institute, Korea District Heating Corporation, 92 Gigok-ro, Yongin, Gyeongi 17099, South Korea
[*]E-mail: kimjg@skku.edu

Received: 18 February 2020 / *Accepted:* 9 April 2020 / *Published:* 10 June 2020

In this case study, we optimized cathodic protection (CP) design for river-crossing district heating (DH) pipeline under the Han River. This pipeline is not electrically insulated with other adjacent pipelines. Therefore, additional consideration for CP current loss to connected pipelines at both sides (North and South side) is needed. Furthermore, there are some limitations on anode installation. For these reasons, computational analysis of CP design was performed considering environmental factors. The minimum current for CP of river-crossing DH pipeline was found to be 100 A, although theoretical calculation result was 74 A. This might be due to the following three reasons. First, the distance of the center area is too far from both anode groups. Second, electrically connected south/north pipe can absorb some CP current. Third, the three pipelines are too close to each other. Thus, incorporating practical corrosion properties of metal and environmental factors in the computational analysis can improve the reliability of CP design for a pipeline.

Keywords: Cathodic Protection; District Heating; Potentiodynamic Polarization test; Computational Analysis; River-Crossing Pipeline

1. INTRODUCTION

District heating (DH) system plays a significant role in increasing current energy efficiency to meet future energy demands [1, 2]. DH systems are composed of a network of pipes connecting buildings in a whole city. They can be supplied from centralized plants [3, 4]. The safety of a DH system is one of the priority factors because pipelines are installed under the civil area. For this reason, DH pipelines are applied using thick thermally insulated coating layer for safety to minimize heat loss. Generally, the coating has two layers, a polyurethane foam (PUR) layer and a high-density polyethylene (HDPE) layer, as shown in Figure 1(a). However, in case of a long river crossing line, it can contain four layers: PUR, outer pipe, PUR, and HDPE (Figure 1(b)) [5]. In the early stage, these coating layers can effectively prevent corrosion by blocking the corrosive environment when the coating is maintained perfectly [6, 7]. However, the HDPE is susceptible to sudden mechanical damage and the PUR can be degraded by heat, humidity, and oxygen during its long operating time [8-10]. For this reason, cathodic protection (CP) has recently attracted much attention to protect DH pipelines from unexpected corrosion failure.

CP has been used as a primary method in the control of metal corrosion in conjunction with organic coating. A properly maintained system can provide protection in accordance with the designed structural life [11, 12]. CP systems are divided into the two standard types: sacrificial anode CP (SACP) and impressed current CP (ICCP). In the SACP system, the anode has more negative electrochemical potential than the protected structure. The ICCP-system has a power supply (rectifier) that generates larger potential difference between the anode and the structure than SACP, thereby permitting a greater current flow to the bigger structure that is being protected [13, 14]. The sacrificial anode system has several advantages such as easy installation and insensitive to overprotection. However, this system cannot be controlled. The DH pipeline is buried in soil and operated for a long time. Control of CP system is very important. Therefore, ICCP is more suitable than SACP for CP of DH pipelines.

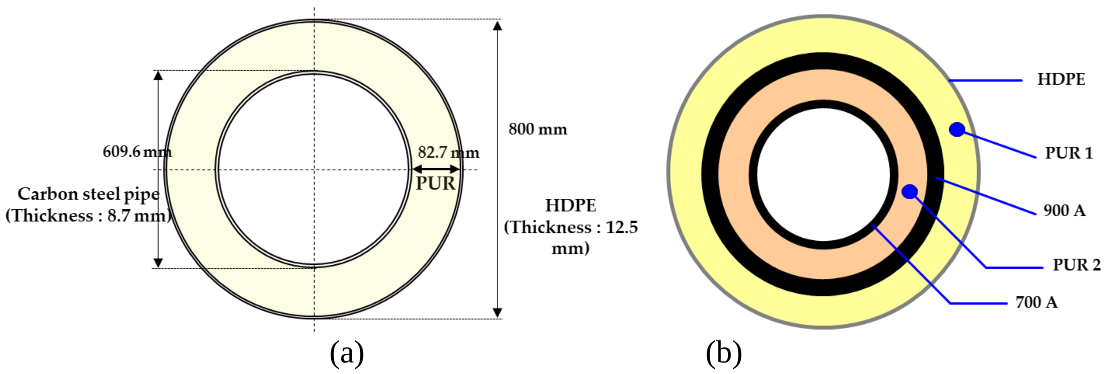


Figure 1. Schematic diagrams of (a) two layers, (b) four layers of DH pipeline coatings.

When applying CP to DH pipeline, there are some considerations due to the thick coating layers of pipelines. It is hard to verify if the CP current can reach the pipe surface because the heavy coating can act as an obstacle to current flow [15]. Especially, in the case of the river-crossing pipeline which has four coating layers, it is reasonable to apply the CP design to the outer pipe (900 A) rather than the inner pipe (700 A). Buried pipelines are generally electrically insulated for specific length or area. Thus, it is easy to design CP using proper environmental data. On the other hand, in case of DH pipeline, there is no electrical insulation between entire pipelines. Thus, CP design should be considered the leakage of CP current to non-target area. For this reason, additional CP design methods such as computational analysis should be applied to optimize the design.

In this case study, we designed CP for river-crossing DH pipeline under the Han River (Seoul, South Korea, constructed in 1987) as shown in Figure 2. The pipeline is not electrically insulated with other adjacent pipelines. Therefore, additional consideration for CP current loss to connected pipelines at both sides (North and South side) is needed. There are some limitations on anode installation. The anode should be installed at both sides due to the deep/long width of the Han River and high installation/maintenance cost. For these reasons, computational analysis was conducted to CP design considering these problems. Additionally, to improve the reliability of simulation results, several essential environmental factors were considered and used as input data, such as polarization data for real materials using electrochemical test and appropriate environmental parameters.

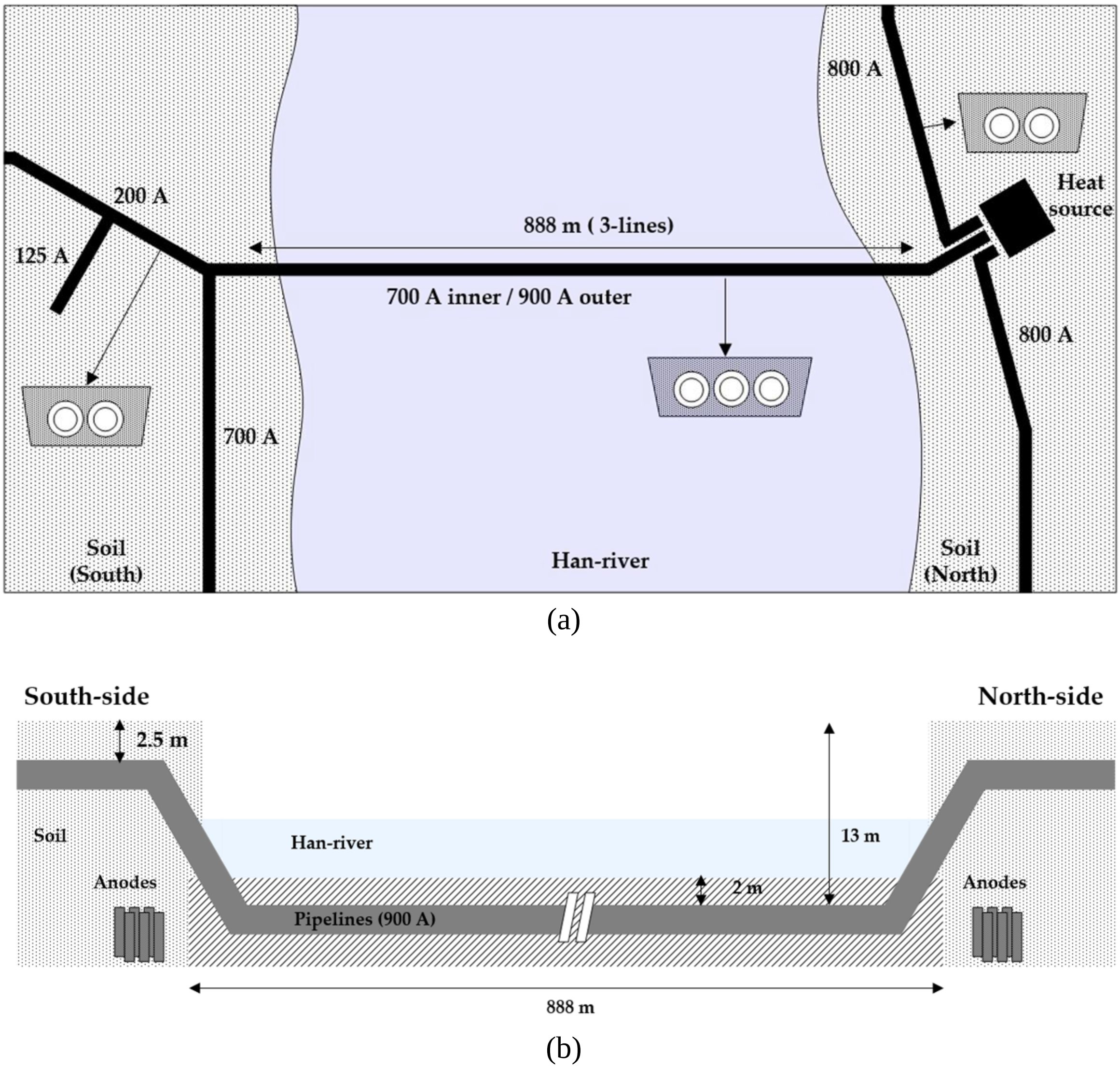


Figure 2. Schematic diagram of river-crossing DH pipeline of the Han River: (a) Whole area with adjacent pipelines, (b) cross-sectional image of river-crossing pipeline.

2. MATERIALS AND METHODS

2.1 Specimen and test solution

The corrosion environment used was a river water acquired from the CP installation site at the Han River. Table 1 gives chemical composition of the river water. The temperature of the solution was controlled to be 25, 60, 80, and 95 °C considering the average temperature range of DH pipeline (return path).

A welded mild steel was used as a test specimen for conservative CP design. The welded specimen consisted of base metal, heat affected zone, and weld metal. It was used during testing to calculate the required CP current. Table 2 shows the chemical composition of the SPW400 (mild steel). Table 3 shows welding methods used in all experiments. The surface of the specimen was polished with 600-grit silicon carbide (SiC) paper, degreased with ethanol, and dried with N_2.

Table 1. Chemical Composition of the Han River water

Ca^{2+} (ppm)	Cl^- (ppm)	NO_3^{2-} (ppm)	SO_4^{2-} (ppm)	pH
21	18.6	8.3	14.7	6.8

Table 2. Chemical Composition of SPW400 (wt.%)

Fe	C	P	S
Balance	0.25 Max.	0.04 Max.	0.04 Max.

Table 3. Welding procedure specification

Welding process	GTAW
Joint design	Single V joint with a 60˚ included angle and a 1.6 mm root face
Electrode	GTAW ER70S-G
Voltage	12-15 V
Current	100-180 A
Polarity	DSCP
Travel speed	20-30 cm/min
Welding atmosphere	Ar, 15-25 L/min

2.2 Electrochemical Test Methods

All electrochemical experiments were performed using a three-electrode system in a 1000 mL Pyrex glass corrosion cell connected to an electrochemical apparatus. These test specimens were connected to a working electrode. A graphite rod was used as the counter electrode and a saturated calomel electrode (SCE) was used as the reference electrode. The area of the test specimen exposed to the electrolyte was 1 cm^2 (1 × 1 cm). The open-circuit potential (OCP) was established within 3 hours to carry out the electrochemical test. Potentiodynamic polarization tests were carried out in accordance with ASTM G5 using a VMP2 (Bio-Logic Science Instruments, France) with a potential sweep of 0.166 mV/sec from an initial potential of -1400 mV vs. the reference to a final potential of 300 mV vs. OCP [16].

2.3 CP design and computational analysis method

To achieve reliable simulation results, parameters such as soil resistivity and coating breakdown factor were measured in the installed field. The Wenner four-pin method was used to obtain soil resistivity under the Han River and connected north/south area, respectively. DCVG (Direct Current Voltage Gradient) measurement was conducted to analyze the coating breakdown factor for the river-crossing pipeline. The diameter of inner pipelines was 700 A (711.2 mm). However, the practical CP applied pipeline should be outer pipelines with a diameter of 900 A (914.4 mm) because the CP current cannot go through thick coating layers. In other words, the inner line would be safe when the outer line is protected perfectly. For this reason, in this study, we designed and calculated surface area for outer pipelines.

The computational analysis tool BEASY S/W (BEASY Ltd., Southampton, England) based on the boundary element method (BEM) was used to conduct 3D modeling and computational analysis of the DH pipeline. The required CP current (I_{req}) for the pipeline was calculated considering the current density of the real material measured by electrochemical tests. The cathodic polarization curve was used as input data for the simulation. It was obtained from the potentiodynamic polarization test which incorporated environmental parameters.

3. RESULTS AND DISCUSSION

3.1. Potentiodynamic Polarization Tests

Electrochemical analysis was conducted to obtain corrosion property of a material in the Han River environment. Potentiodynamic polarization test can characterize a metal specimen based on its current-potential relationship. The test is used to determine corrosion characteristics of metal specimens in aqueous environments [16]. Results of the potentiodynamic polarization test are shown in Figure 3. The anodic and cathodic current density continually increase until 80 °C due to the chemical reaction accelerating. While, above the 80 °C, the cathodic current density dramatically decreased because the oxygen for cathodic reaction could not soluble to the solution. The corrosion current density was determined using the Tafel extrapolation method. As shown in Table 4, the maximum corrosion current density was measured at a temperature of 80 °C. Therefore, to design conservatively, the cathodic polarization curve at 80 °C which contained corrosion properties of real material was used as input data for computational analysis.

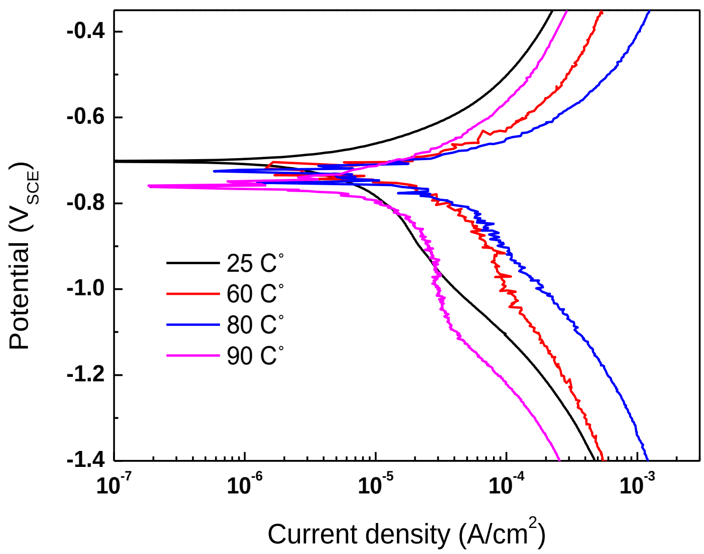


Figure 3. Results of potentiodynamic polarization test in the Han River solution.

Table 4. Results of potentiodynamic polarization test in the Han River solution

Temperature (℃)	**Corrosion potential (mV$_{SCE}$)**	**Corrosion current density (μA/cm^2)**
25	-704	4.5
60	-712	26.5
80	-724	46.6
90	-759	9.6

According to previous reports [6, 17], the maximum CP potential criteria for DH pipeline was recommended to be -1350 V$_{SCE}$ due to the high temperature and corrosive elements in ground water. However, in case of this study, the river water is milder than ground water. Thus, the CP potential criteria should be re-considered. Table 4 shows CP current density variation of mild steel at 80℃ according to the potential. It was revealed that the maximum CP potential criteria in this environment could be applied to -780 mV$_{SCE}$ (-850 mV$_{CSE}$) which was the general CP potential criteria because that potential could obtain enough design life for the pipeline. Additionally, the minimum CP potential criteria should be considered. According to the international standards such NACE (RP0169), ARAMCO (SAES-X-400), and BSI (BS 7361-1), the overprotection range of steel pipeline ranges from -2.5 V$_{SCE}$ to -5 V$_{SCE}$ [18, 19, 20]. Although the standards, there is a concern about hydrogen embrittlement. Therefore, the insulating panel should be applied when the anodes will be installed to suppress the excess current absorption at the pipeline which is the closest to the anodes. It is general method when applying ICCP at the large-scale structures [11]. However, in this case study, the key point is the center section of the river crossing pipeline whether the CP current could be reached, so the installation of panel was omitted. Therefore, the final CP potential criteria for this study should be applied to -780 ~ -2500 mV$_{SCE}$ (-850 ~ -2570 mV$_{CSE}$) range.

Table 5. CP current density variation of mild steel at 80°C according to the potential

Potential ($mV_{SCE/CSE}$)	**Corrosion current density ($\mu A/cm^2$)**	**Corrosion rate (mm/year)**	**Design life (year)**
-675/-745 (Without potential)	46.6	0.270	17.1
-780/-850	16.2	0.094	49.2
-830/-900	9.3	0.054	85.7
-880/-950	5.4	0.031	147.6
-930/-1000	3.0	0.017	265.7
-1000/-1070	1.41	0.008	565.3

3.2. Cathodic protection design and computational analysis

To design CP, the required CP current (I_{req}) should be calculated. The required current of CP is the current for decreasing the surface potential of object structure to appropriate CP potential criteria. Parameters for calculating required current of CP are surface area, coating breakdown factor, and corrosion current density. It can be calculated as below [21]:

$$I_{req} = A_p \cdot C_b \cdot I_{corr} \quad (1)$$

where A_p is the surface area of structure which contains 10% of additional surface area, C_b is coating breakdown factor, and I_{corr} is corrosion current density of material in CP environment. These parameters and calculated I_{req} (required CP current) are listed in Table 6. Theoretical calculation indicated that 74 A of CP current could satisfy CP criteria. Because of some structural limitations mentioned above, anodes must be installed at both sides of pipelines. Therefore, an anode (6 for each group) at each side has 37 A.

Table 6. Parameters and calculated required CP current

Applied current density (i_{app})	**Surface area with 10% safety factor (A_{pipe})**	**Defect ratio (C_{defect})**	**Required current (I_{req})**
0.46 A/m^2	8,598 m^2 (Diameter: 914.4 mm)	1.87 %	74 A

Figure 4 shows 3D modeling of river-crossing DH pipeline. The DH pipeline consists of three lines (supply, return and spare). The diameter was 900 A (914.4 mm) as mentioned above. Anodes are placed at both sides of the pipeline using deep well anode bed method. The depth of the anode from ground was 60 m as the general depth of a deep well [12]. There were no electrically affecting objects around the river-crossing pipeline except the connected pipelines. The whole model was divided into three zones according to soil resistivity. The average value of soil resistivity under the river was 4400 ohm-cm^2 and that of north/south pipelines was 9000 ohm-cm^2 which was the average value of field investigation. The number of meshes on the modeling was 69,076 ea. Based on this 3D modeling, simulation was conducted.

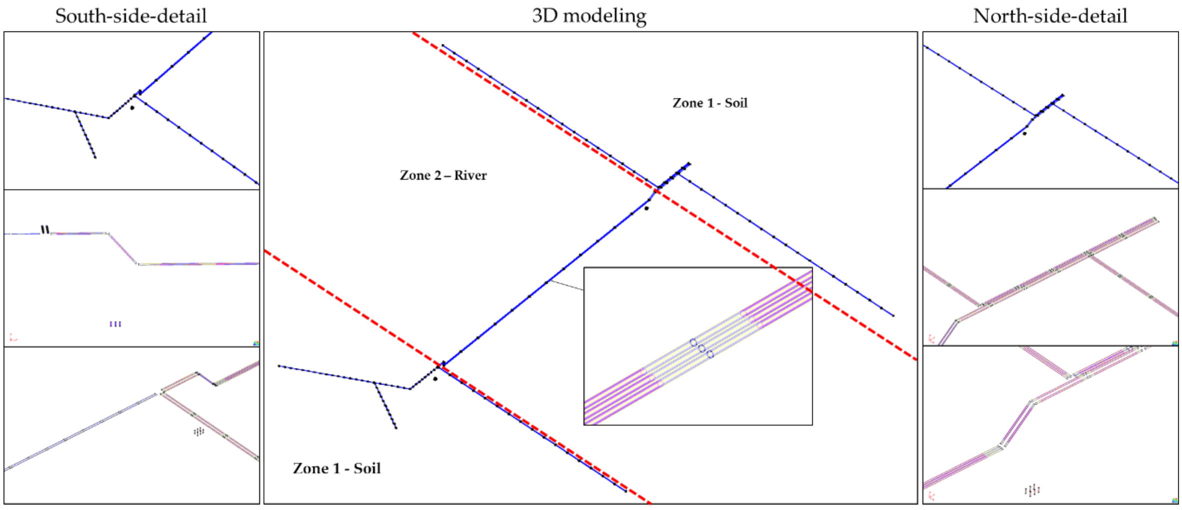
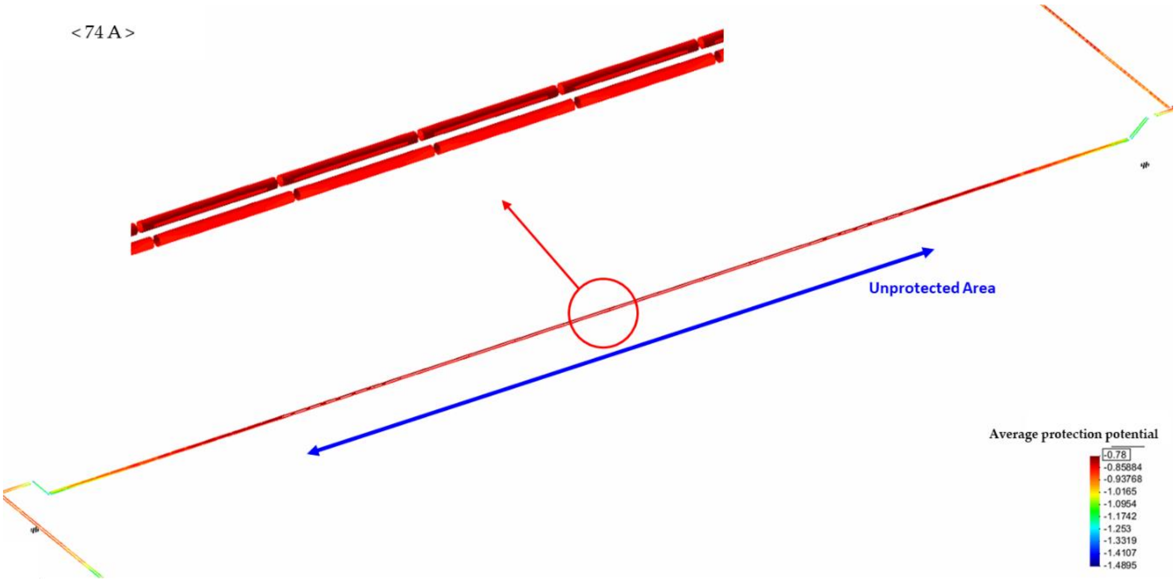
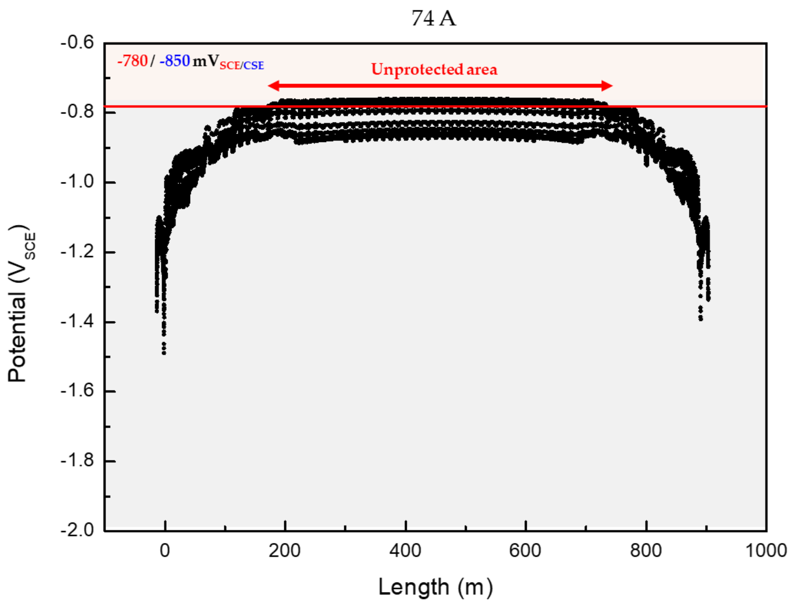


Figure 4. 3D modeling of river-crossing pipeline with adjacent pipelines.

As shown in Figure 5, the result of 74 A could not satisfy the CP potential criteria and unprotected area was revealed in the center of the river-crossing DH pipeline. The maximum potential of the river-crossing pipeline was -760 mV_{SCE} which is higher CP potential than CP criteria (-780 mV_{SCE}). In addition, especially, the center pipe is not satisfied the CP criteria among the 3-line-pipe, so it is invisible at the Figure 5(a). On the other hand, both sides of a directly upper area from anodes indicated the lowest surface potential. The minimum values which is about -1,490 mV_{SCE} are revealed at the upper side of both anodes. And, it is over the -2,500 mV_{SCE} which was mentioned above, so there is seldom hydrogen effect at this part [18-20]. Each point of the Figure 5(b) indicates the mesh points of the target pipelines. As same as 3D results, the part of central area was not satisfied the CP criteria. This inequality potential distribution and unsatisfied CP potential came from three structural reasons [11, 13]. First, the distance of the center area was too far from both anode groups, making it hard for CP current to reach the center. Second, the electrically connected south/north pipe absorbed some CP current. This was shown in the simulation result of connected area which had lower surface potential compared to corrosion potential. The third reason was related to the three pipelines that were too close to each other. Thus, the CP current could not reach the center pipeline. It was absorbed preferentially by both sides of the pipeline.



(a)

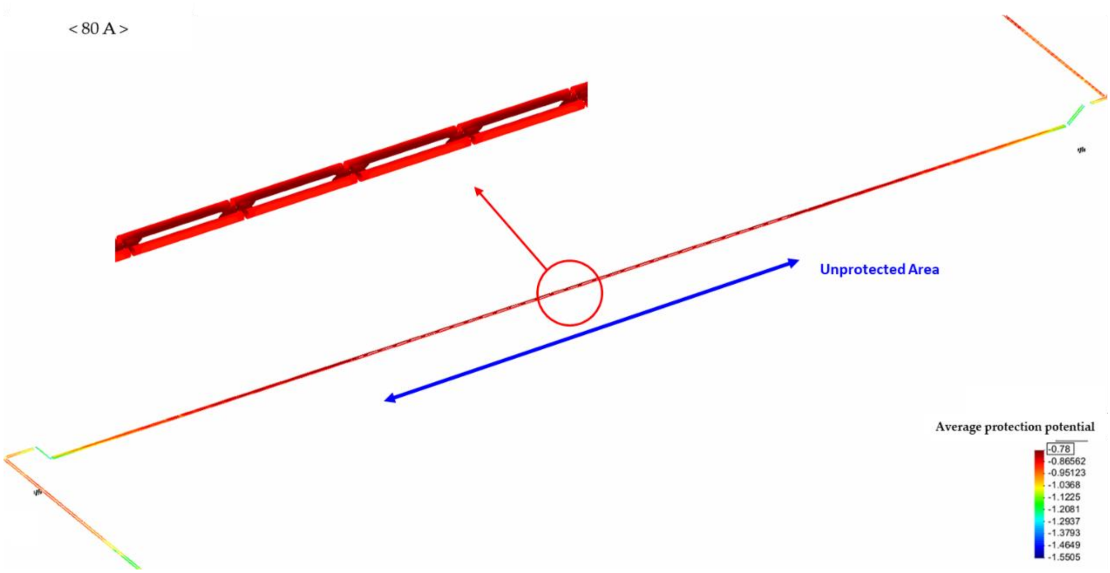


(b)

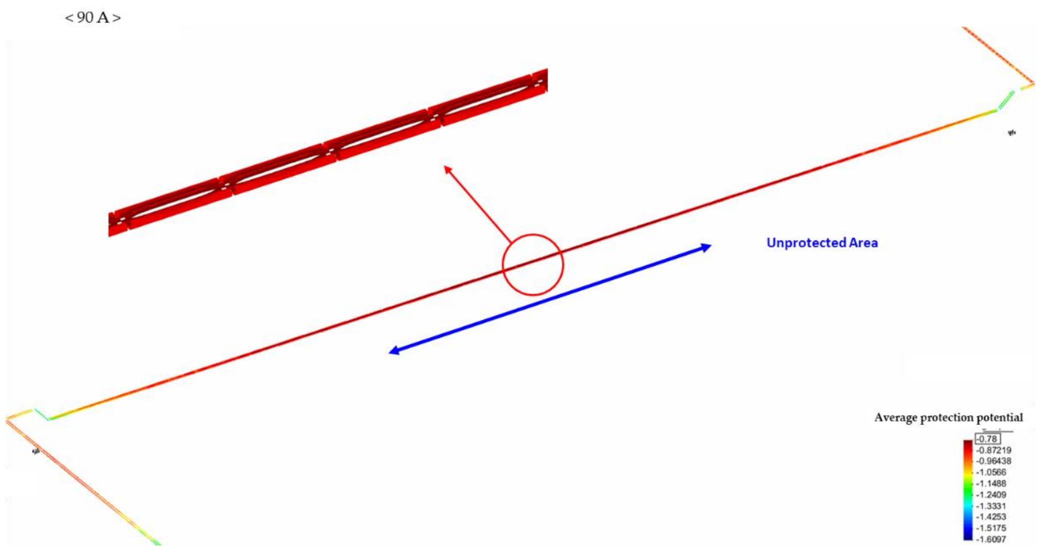
Figure 5. Simulation results at 74 A of CP current. (a) Results in 3D modeling, (b) Potential distribution of the pipeline according to the length of pipeline.

Despite these structural problems, the river-crossing DH pipeline has already been constructed and operating. Thus, it is hard to revise. The only solution to apply CP to the whole river-crossing DH pipeline is by increasing the required CP current and verify it using simulation. Only the theoretical calculation has limitations due to the uncertain CP current absorption of non-target pipelines and two different soil resistivity section, therefore the required CP current was increased 80, 90, 100, and 110 A to simulate the CP condition of the pipeline. Simulation results according to CP current increase are shown in Figure 6 and 7. According to results at 80 and 90 A, the pipeline in center area which is the furthest from both sides of the anode is not satisfying CP criteria due to the three structural factors mentioned above. The maximum potentials of 80 and 90 A results are -763 and -773 mV_{SCE}, respectively. As shown in Figure 6(a) and (b), the center pipe among the 3-line-pipe shows the partially satisfied the CP criteria when compare with the results of 74 A. Likewise, in Figure 7(a) and (b), the unprotected area is reduced as the current increasing. As shown in Figure 6(c) and (d), Figure 7(c) and (d), the results at 100 and 110 A satisfied CP criteria, which show -784 and -789 mV_{SCE}. The potential of the whole area was under -780 mV_{SCE} (-850 mV_{CSE}). Additionally, the minimum CP potential at the both sides were about -1,633 and -1,725 mV_{SCE} which are safe to hydrogen embrittlement.

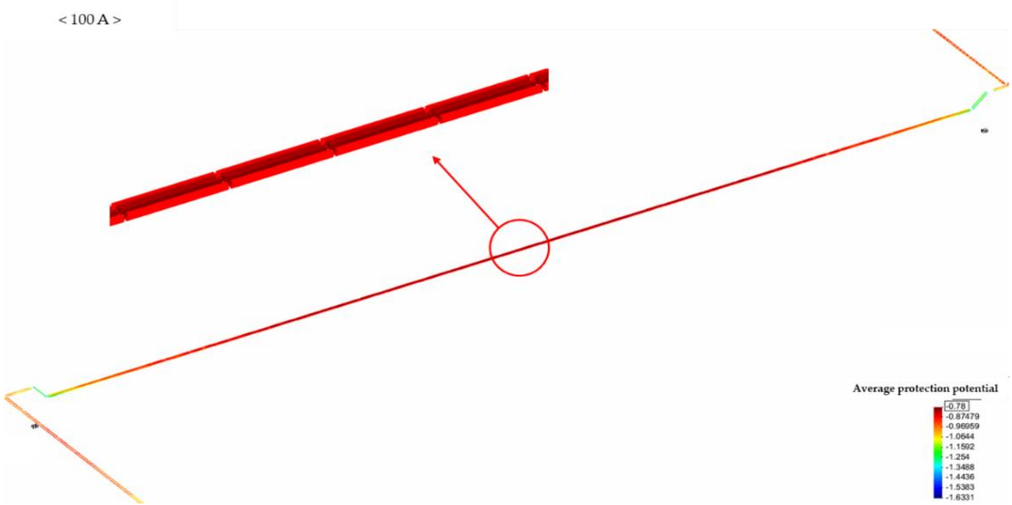
Consequently, in this case study, it was revealed that the additional current to overcome structural limitations is 26 A. Consequently, the minimum current for CP of river-crossing DH pipeline is 100 A, although the theoretical calculation result was 74 A. Simulation result of CP current at 100 A was verified in that CP criteria were satisfied in the center area known to be the most vulnerable point of the pipeline.



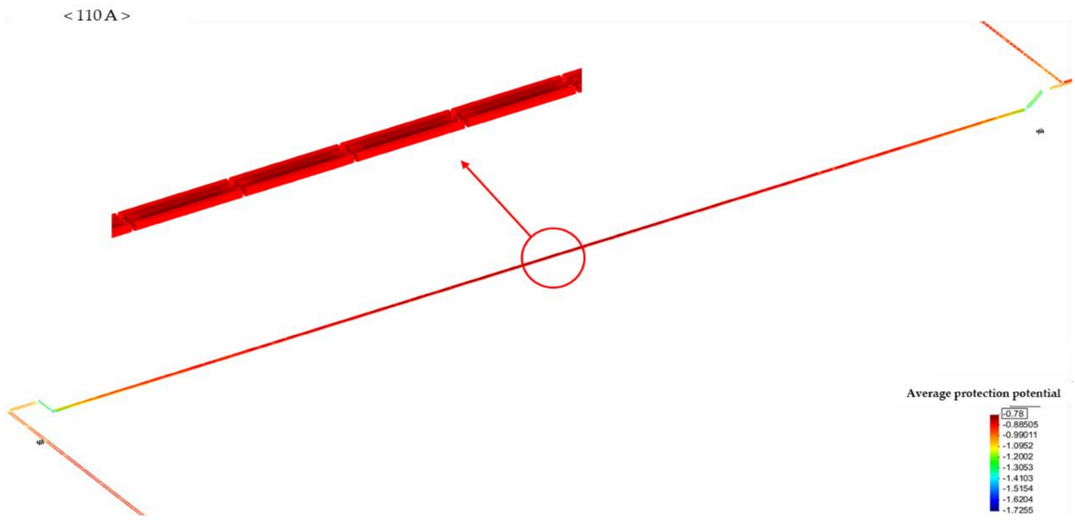
(a)



(b)

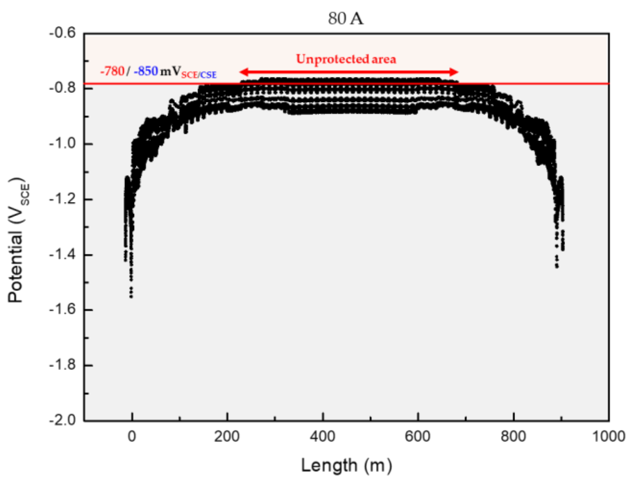


(c)

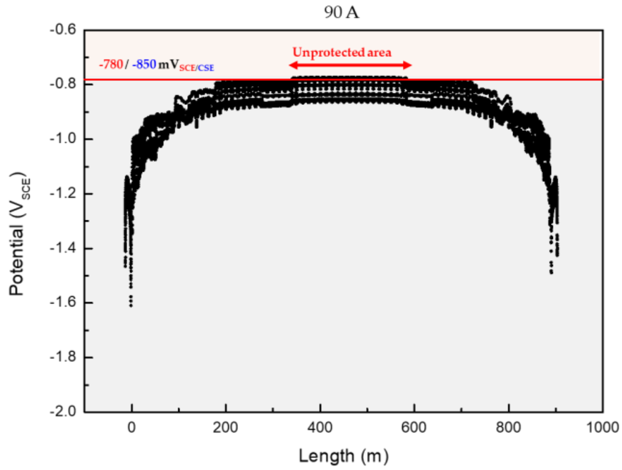


(d)

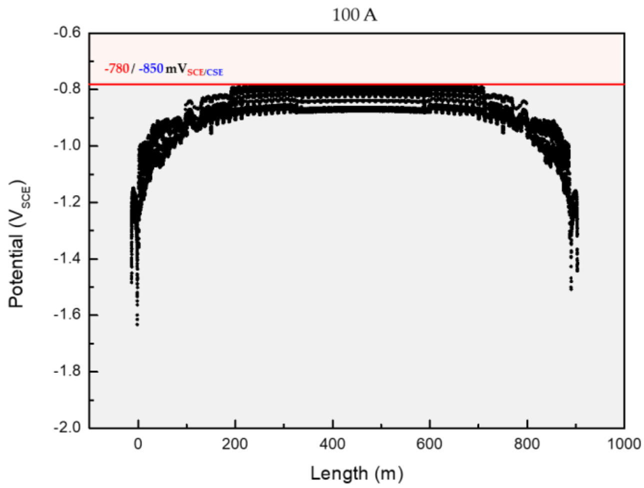
Figure 6. Simulation results in 3D modeling according to CP current: (a) 80 A, (b) 90 A, (c) 100 A, (d) 110 A.



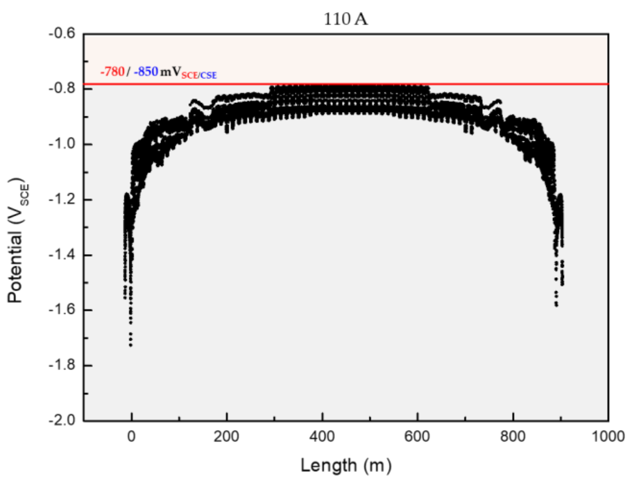
(a)



(b)



(c)



(d)

Figure 7. Simulation results according to the CP current and potential distribution of the pipeline according to the length of pipeline: (a) 80 A, (b) 90 A, (c) 100 A, (d) 110 A.

4. CONCLUSIONS

In this study, a reliable CP design method for existing river-crossing DH pipeline of the Han River is described considering environmental/structural factors. Computational analysis was performed to verify and optimize the CP design. According to analysis results, the following conclusions were drawn:

◆ Electrochemical analysis was conducted to obtain the corrosion property of the material in the Han River environment. The maximum CP potential criteria for DH pipeline was recommended to be -1350 V_{SCE}. However, in this study, the river water was milder than ground water. Thus, the final CP potential criteria should be at -780 ~ -2500 mV_{SCE} (-850 ~ -2570 mV_{CSE}).

◆ Results of simulations using the theoretical method failed to satisfy CP criteria. There are three reasons. First, the distance of the center area is too far from both anode groups. Second, the electrically connected south/north pipe absorbed some CP current. Third, the three pipelines are too close to each other.

◆ The only way to solve the problem is by increasing CP current in an effective way because of limited structural factors. Consequently, an additional 26 A should be applied to satisfy the CP criteria at the center area.

◆ Incorporating practical corrosion properties of metal and environmental factors in the computational analysis can improve the reliability of CP design for a pipeline. Additionally, computational analysis is an essential step for credible and effective CP design.

◆ The basic CP design methods which conducted in this study could be applied to almost situations. However, after the basic CP design, detail design should be conducted according to a situation. This case study can be a good reference to other studies as below; (1) when apply CP to already buried pipeline, (2) river-crossing pipeline according to the river condition, (3) non-insulating pipeline between both sides of adjacent pipe.

AUTHOR CONTRIBUTIONS

Conceptualization, M.S.H., Y.S.J., W.C.K.; Methodology, M.S.H.; Software, M.S.H.; Validation, M.S.H. and J.G.K.; Formal analysis, M.S.H.; Investigation, M.S.H., Y.S.J, W.C.K; Resources, M.S.H.; Data curation, M.S.H.; Writing—original draft preparation, M.S.H.; Writing—review and editing, M.S.H. and J.G.K.; Visualization, M.S.H.; Supervision, J.G.K.; Project administration, M.S.H. and J.G.K.;

FUNDING

This research was supported by the program for fostering next-generation researchers in engineering of National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (2017H1D8A2031628).

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

References

1. A. Gebremedhin, *Renew. Sust. Energ. Rev.*, 30 (2014) 230-236.
2. M. Morandin, S. Harvey, *Energy*, 65 (2014) 209-220.
3. P. Gładysz, A. Ziębik, *Energy*, 62 (2013) 12-22.
4. H. Lund, S. Werner, R. Wiltshire, S. Svendsen, J.E. Thorsen, F. Hvelplund, B.V. Mathiesen, *Energy*, 68 (2014) 1-11.
5. S.Y. Choi, K.Y. Lee, J.B. Lee, C.B, Shin, M.J. Park, *Appl. Therm. Eng.*, 30 (2010) 2067-2072.
6. M.-S. Hong, Y.-S. So, J.-G. Kim, *Materials*, 12 (2019) 1761.
7. J.G. Kim, Y.W. Kim, M.C. Kang, *Corrosion*, 58 (2002) 175-181.
8. Y.-S. Choi, M.-K. Chung, J.-G. Kim, *Mater. Sci. Eng. A*, 384 (2004) 47-56.
9. N. Yarahmadi, J. Sällström, *14th International Symposium on District Heating and Cooling*, (2014).
10. R. Fessler, A. Markworth, R. Parkins, *Corrosion*, 39 (1983) 20-25.
11. M.S. Hong, J.H. Hwang, J. Kim, *Corrosion*, 74 (2017) 123-133.
12. W. von Baeckmann, W. Schwenk, W. Prinz, *Handbook of cathodic corrosion protection*, Elsevier, (1997) Huston.
13. V. Cicek, *Cathodic protection: Industrial solutions for protecting against corrosion*, John Wiley & Sons, (2013) New Jersey.
14. D.A. Jones, *Principles and prevention of corrosion*, Prentice Hall, (1996) New Jersey.
15. *Effectiveness of cathodic protection on thermally insulated underground metallic surfaces*, NACE Technical Committee Report No. 24156, (1992).
16. American Society for Testing and Materials, *ASTM G5-14: Standard Reference Test Method for Making Potentiodynamic Anodic Polarization Measurements*, ASTM, (2014) Pennsylvania.
17. J.G. Kim, Y.W. Kim, *Corros. Sci.*, 43 (2001) 2011-2021.
18. *Control of External Corrosion on Underground or Submerged Metallic Piping Systems*, NACE Standard RP0169, (2013).
19. *Cathodic Protection of Buried Pipelines*, Saudi Aramco Engineering Standard SAES-X-400, (2011).
20. *Cathodic protection - Part 1: Code of practice for land and marine applications*, British Standards Institution, (1991).
21. D.N. Veritas, *Cathodic protection design, Recommended Practice DNV-RP-B401*, DNV, Norway, 2010