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Optimization of Cathodic Protection System for River-Crossing District Heating Pipeline using Computational Analysis: Part II. The effective location of anodes

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In the previous study, we designed cathodic protection (CP) for river-crossing District Heating (DH) pipeline with appropriate environmental factors. The study verified the satisfaction of the CP criteria at the target structure with fixed anode location. However, consideration of the optimized anode location is a very important factor; therefore, in this case study, we used computational analysis to optimize the location of anode for effective CP. The CP potential variation was observed according to the position of the west anode. In the case of 74 A, which is the current calculated by theoretical method, the maximum CP potential decreases by increasing the anode distance up to 400 m; however, it did not satisfy the CP criteria in all anode locations. The 100 A current, which is the optimized CP current without anode movement from the previous study, showed a similar tendency. All of the results satisfied the CP criteria, and the lowest potential was observed at 500 m. In all of the studied cases, it can be concluded that the optimized distance of anode is between 400 and 500 in the range 74 and 100 A. Consequently, the optimized CP design can be achieved at the anode location of 400 m with CP current of 83 A. This study shows the significance of anode location and distribution to structure in CP design. Obviously, computational analysis should be conducted to obtain more stable and reliable CP design in the real field.

Keywords: Polarization test; Computational Analysis; River-Crossing Pipeline; Cathodic Protection; Anode; Impressed Current Cathodic Protection;

1. INTRODUCTION

A modern district heating (DH) system can supply a whole city, which is an eco-friendly and high-efficiency solution, compared with the conventional heating system that uses boilers or direct electric heating. The heat will be distributed using pre-insulated pipes buried directly into the ground, and at each building [1-3]. The inner environment of the DH pipeline is heating water that is purified using chemical/physical methods [4, 5]. The corrosive ions, such as chloride ion and sulfate ion, are removed, and oxygen is maintained below 200 ppb [6]. It is quite a mild environment, so it is hard for sudden corrosion fracture to occur starting from the inner environment. On the other hand, although the outer environment has multiple pre-insulating layers, the corrosion failure could occur from coating defects, because the pipeline was installed and operated for a long period without maintenance [7-9]. The DH pipeline is installed under the town, so severe problems could occur, such as hot water/heating supply interruption, and damage of human life. For this reason, applying cathodic protection (CP) to the outer surface of DH pipeline is recently being actively considered.

CP is one of the most widely used methods of corrosion prevention. In principle, it can reduce or prevent the corrosion of any metal or alloy exposed to any electrolyte or soil. Corrosion can be reduced to virtually zero, and a properly maintained system will provide protection indefinitely [10]. In the case of the DH system, the pipelines were installed in a very wide range over a city unit, so it is impossible to apply CP to the entire area of the DH pipeline. For this reason, the CP for DH pipeline focuses on specific areas, such as more corrosive environment, hard to the maintenance or repair, or downtown, where personal injury might occur. The CP could be divided into two methods: sacrificial anode CP, and impressed current CP. Generally, impressed current CP is used for larger structure than sacrificial anode CP [11, 12]. Moreover, the impressed current CP can monitor the CP state in real time, so it is suitable for DH pipelines.

In the previous study [13], we designed CP for river-crossing DH pipeline under the Han River (Seoul, South Korea, constructed in 1987) with appropriate environmental factors. After that, we found the optimized CP current according to the comparison between theoretical calculation and computational analysis. The study verified the satisfaction of the CP criteria at the target structure with fixed anode location. Likewise, in this study, the anodes can only be installed at both sides of the target pipeline due to the deep and wide river; however, they can be moved and installed in soil along the river line, as shown in Fig. 1. Additionally, the consideration of optimized anode location in the limited condition is not only significant to this study, but also for every CP design issue. In particular, in the case of the target structure and non-target structure being adjacent and connected, the anode location is one of the most important variables. Therefore, in this case study, we optimized the location of anode for effective CP using computational analysis.

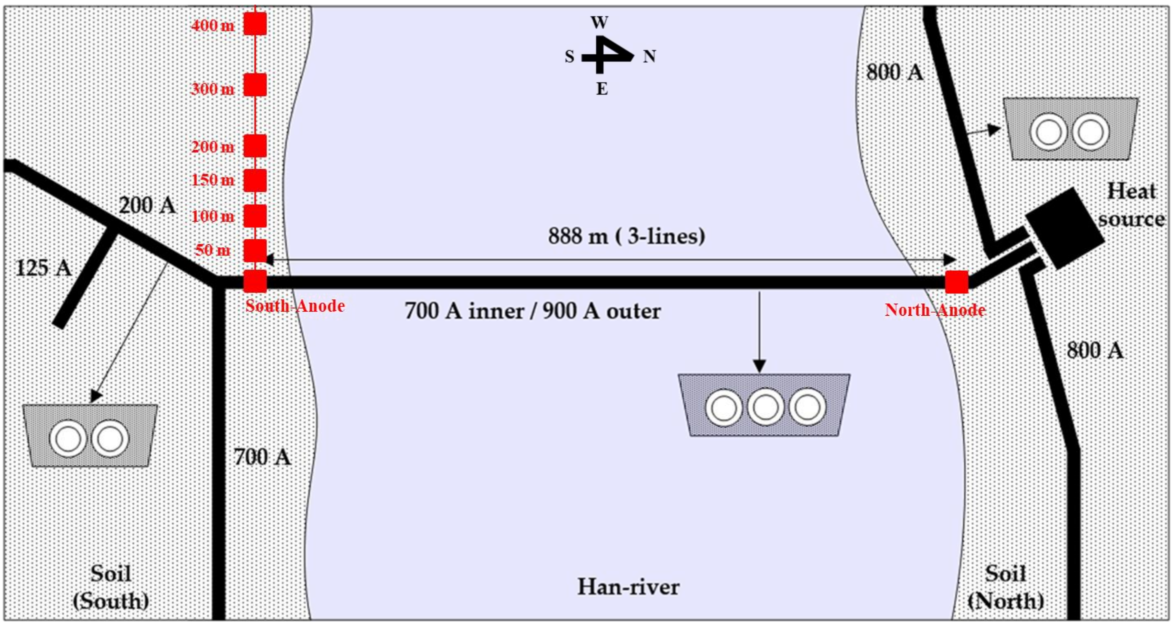


Figure 1. Schematic of river-crossing DH pipeline of the Han River, and the variable location of anodes.

2. MATERIALS AND METHODS

2.1 CP design using environmental factors

Generally, the essential parameters to calculate the required current for CP are the current density of material at that environment, surface area of that structure, and coating breakdown factor [11, 14, 15]. In the case of CP design at the ocean environment, the initial/final recommended current density can be applied for the current density according to international standards, such as DNV [16, 17]. However, it is hard to define the specific condition of soil environment, due to various soil compositions and climatic factors. Therefore, the current density in the real field should be applied to obtain reliable CP design. The current density of the DH pipeline in the environment used the results from previous reports. In the case of surface area, 10 % of additional surface area is added, according to the CP rule-of-thumb [15]. Additionally, the surface area should be calculated using the outer pipeline of 900 A, rather than the inner pipeline of 700 A, because it is difficult for the CP current to go through whole thick coating layers. The initial coating breakdown factor of the DH pipeline is very small, relative to that of the normally coated pipeline. However, this case study targets the installed DH pipeline that was constructed about 30 years ago, so Direct Current Voltage Gradient (DCVG) measurement was conducted to analyze the coating breakdown factor for the river-crossing pipeline. In the case of soil resistivity, it is not an essential factor for CP current calculation; however, it is a significant parameter to determine the distribution of CP current to the structure. The Wenner four-pin method was used to obtain the soil resistivity under the Han River and the connected north/south areas, respectively. The CP criteria of the DH pipeline of -780 / -850 $mV_{SCE/CSE}$ was applied, which was calculated in the previous study [13].

2.2 3D modeling and computational analysis method

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 zones were divided into two sections, to apply the different soil resistivities. Zone 1 contained the DH pipeline, which is the target structure, while zone 2 contained the impressed current CP anode groups and north/south non-target pipelines. The river-crossing DH pipelines consisted of 3 lines, which are the supply, return, and extra pipes, while the non-target pipelines had 2 lines of supply and return. In the case of anode groups, the initial position is the end of both sides of the river-crossing pipeline, and the group contained 6 ea anodes. There are no other pipelines within 3 km of the DH pipeline.

For the computational analysis, the CP current, which was calculated from the current density of the real material, was evenly input to each group of anodes. The cathodic polarization curve that was obtained in the previous study was used as input data for the simulation.

3. RESULTS AND DISCUSSION

3.1. CP design using environmental factors

The coating breakdown factor describes the extent of current density reduction which is the same meaning of corrosion rate reduction due to the application of a coating. It thus describes the anticipated reduction in current density due to the application of an electrically insulating coating. When $C_b = 0$, the coating is 100% electrically insulating, thus decreasing the current density to zero. When $C_b = 1$, it means that the coating has no current reducing properties. The corrosion current density is the material's corrosion property in an environment; therefore, it is important to apply proper corrosion current density when designing the CP. The required CP current to protect a structure within the appropriate CP criteria can be calculated as below:

$$I_{req} = A_p \cdot C_b \cdot I_{corr} \tag{1}$$

where, A_p is the surface area of structure that contains 10% of additional surface area, C_b is the coating breakdown factor, and I_{corr} is the corrosion current density of material in the CP environment. Table 1 shows the parameters and the calculated required CP current. Table 1 also shows that the defect ratio of 0.0187, which was measured by DCGV method, was used in this study as the coating breakdown factor. The corrosion current density was obtained from the previous study [13]. The calculated CP required current was 74 A, which was distributed evenly to the 2 anode groups.

Table 1. Parameters and the calculated required CP current [13].

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	1.87 %	74 A

3.2. 3D modeling and computational analysis (optimization of the anode location)

Figure 2 shows the 3D modeling of the whole pipelines and the variation of anode location. As mentioned above, the location of anode is limited, due to the depth and width of the Han River, and for economic reasons. Because of these considerations, the anode can only be moved along the riverbank. In the case of the north anode area, two non-target pipelines had been installed along the riverbank in the west and east directions. Therefore, it is presumed that there is no effect from moving the anode in both directions, because the CP current from anode would be consumed by the non-target pipeline, rather than the river-crossing DH pipeline. However, in the case of the south anode area, the non-target pipeline had only been installed in the east direction, so the anode could be moved to the west direction, without any concerns about the current consumption for other structure. For this reason, the anode group of the north side was fixed at the origin position, and the south anode group was moved in the west direction, to observe the variation of CP potential in the target structure.

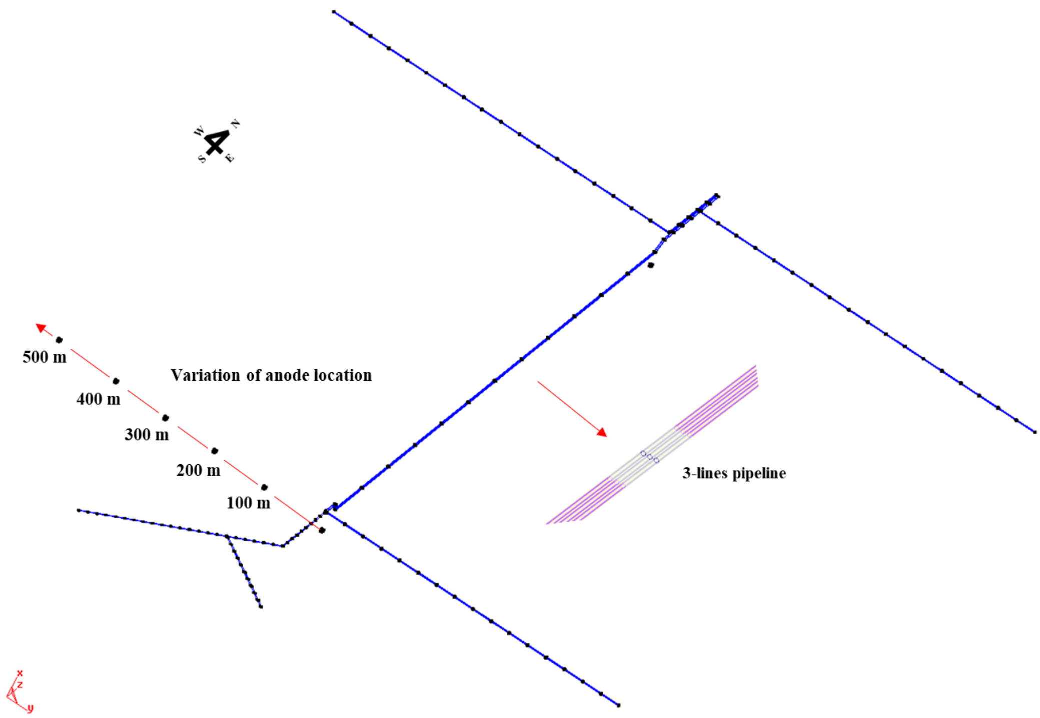
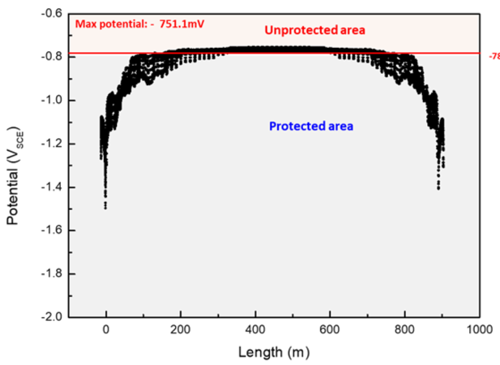


Figure 2. 3D modeling of whole pipelines, and variation of anode location.

Figures 3 and 4 show the results of computational analysis that indicated the potential variation of the river-crossing DH pipeline according to the anode location. The maximum CP potential of the pipeline was decreased with increase of the anode distance from the origin point (0 m). The largest reduction of the maximum CP potential was observed at 400 m, which was -769.9 mV_{SCE}. After that point, the maximum CP potential was increased with distance from the structure. Notwithstanding the modification of anode location, the CP condition of the DH pipeline did not satisfy the CP criteria, due to several structural factors, and therefore additional current should be applied [9-13, 18,19].



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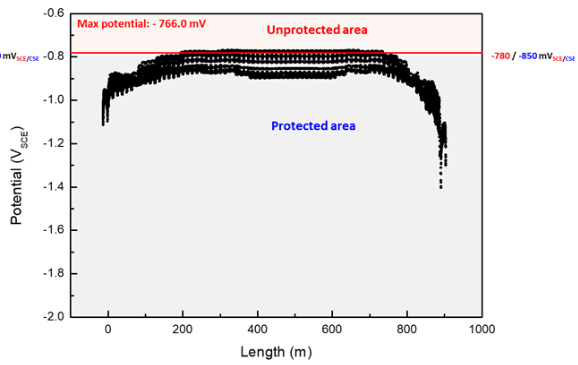

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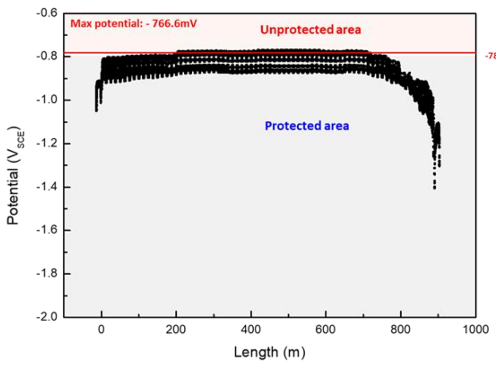

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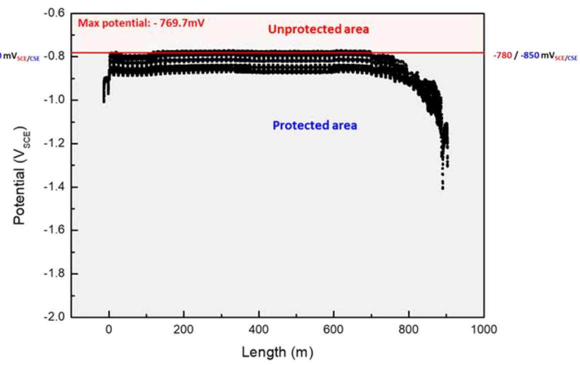

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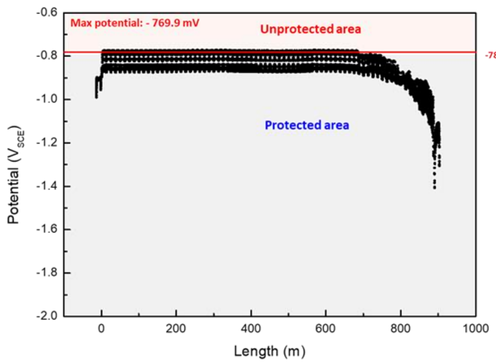

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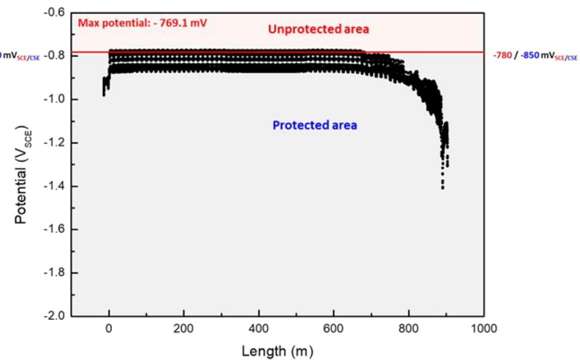

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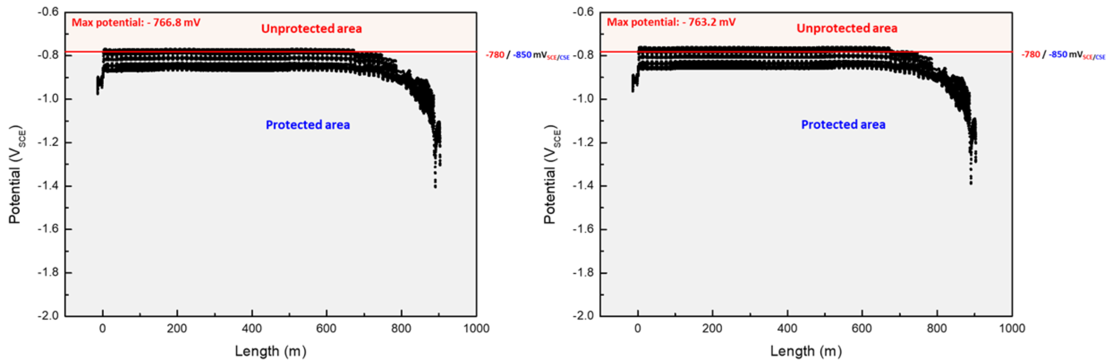


(g) (h)

Figure 3. Simulation results of the DH pipelines at 74 A according to the anode distance; (a) 0 m, (b) 100 m, (c) 200 m, (d) 300 m, (e) 400 m, (f) 500 m, (g) 600 m, and (h) 700 m.

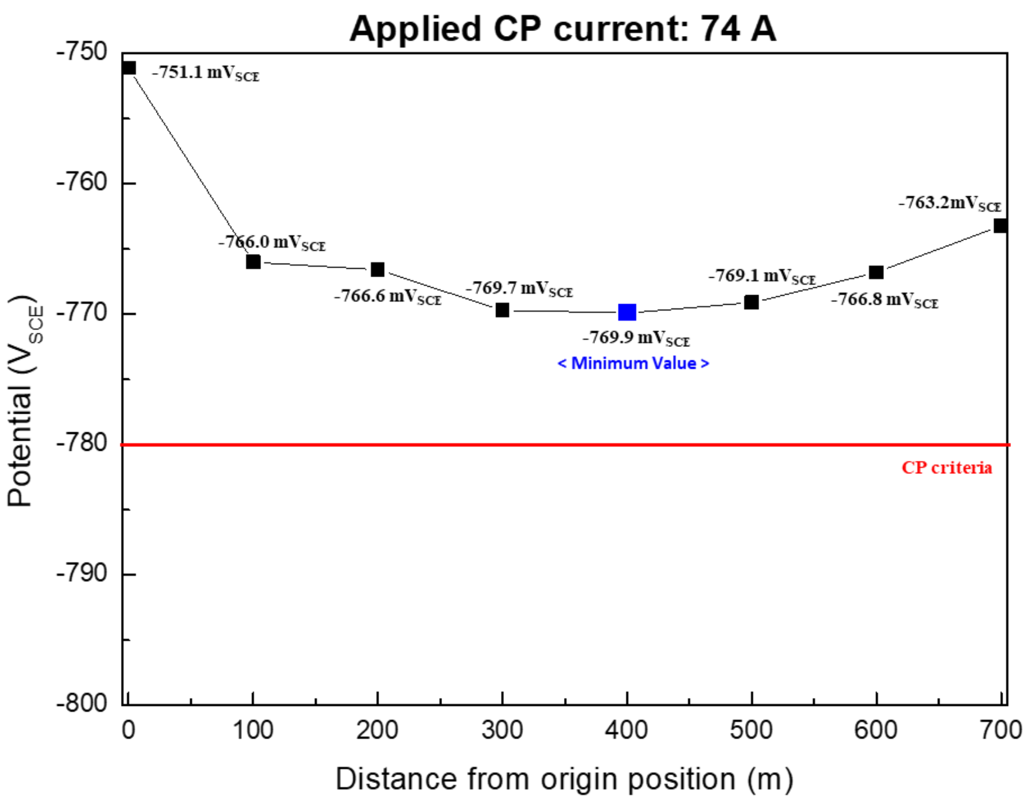
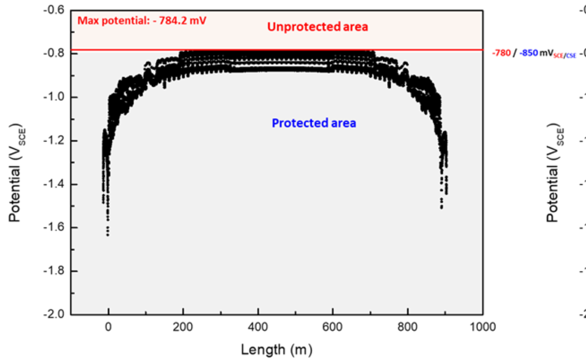


Figure 4. Variation of the maximum CP potential at 74 A according to the anode distance.

The 100 A of optimized CP current without anode movement, which was calculated in the previous study, was applied to observe the variation of the maximum CP potential [13]. Figures 5 and 6 show the simulation results at 100 A, and the variation of maximum CP potential at 100 A, respectively, according to the anode distance. The results show a similar tendency to those of 74 A. All of the results satisfied the CP criteria, and the largest reduction of the maximum CP potential was observed at 500 m, which was -815.3 mV_{SCE}. From both results, it can be concluded that the optimized distance of anode is between 400 and 500 m within the range 74 to 100 A.



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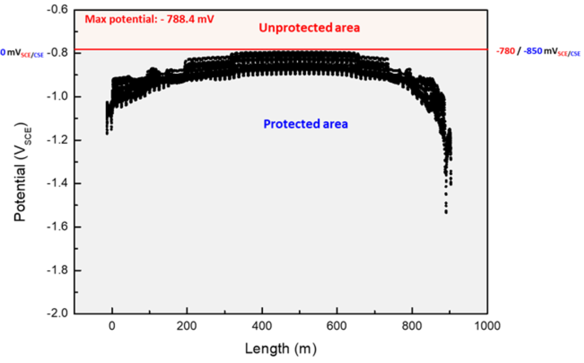

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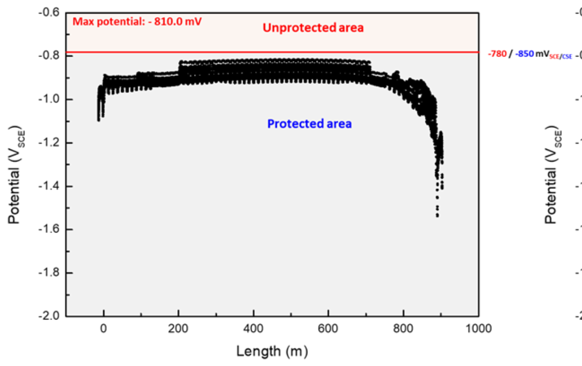

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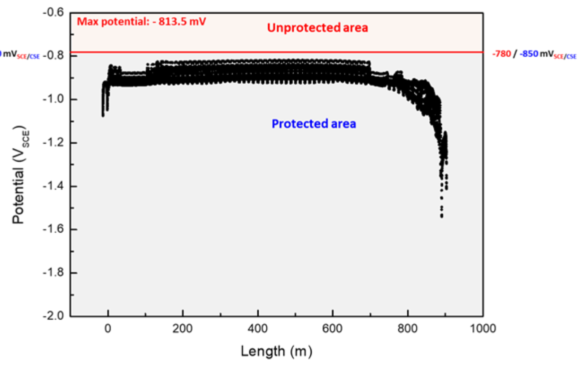

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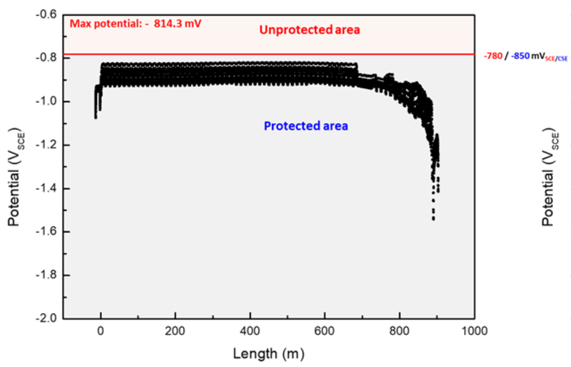

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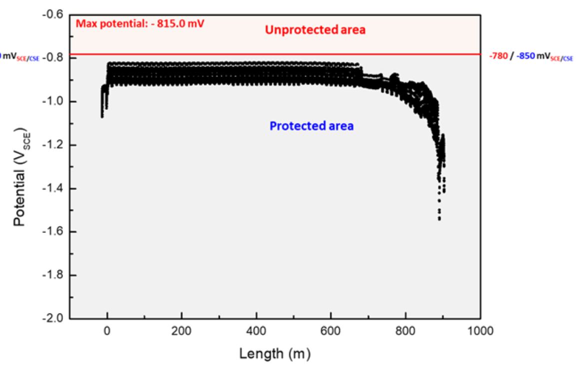

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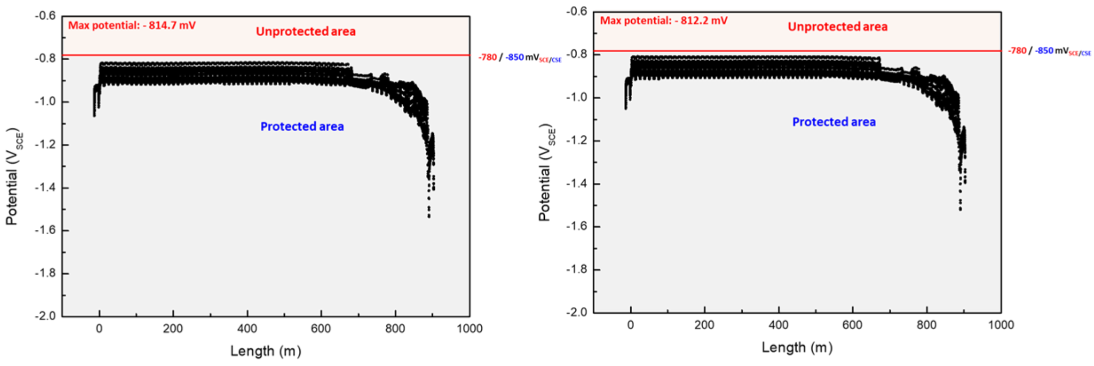

(g) (h)

Figure 5. Simulation results of the DH pipelines at 100 A according to the anode distance: (a) 0 m, (b) 100 m, (c) 200 m, (d) 300 m, (e) 400 m, (f) 500 m, (g) 600 m, and (h) 700 m.

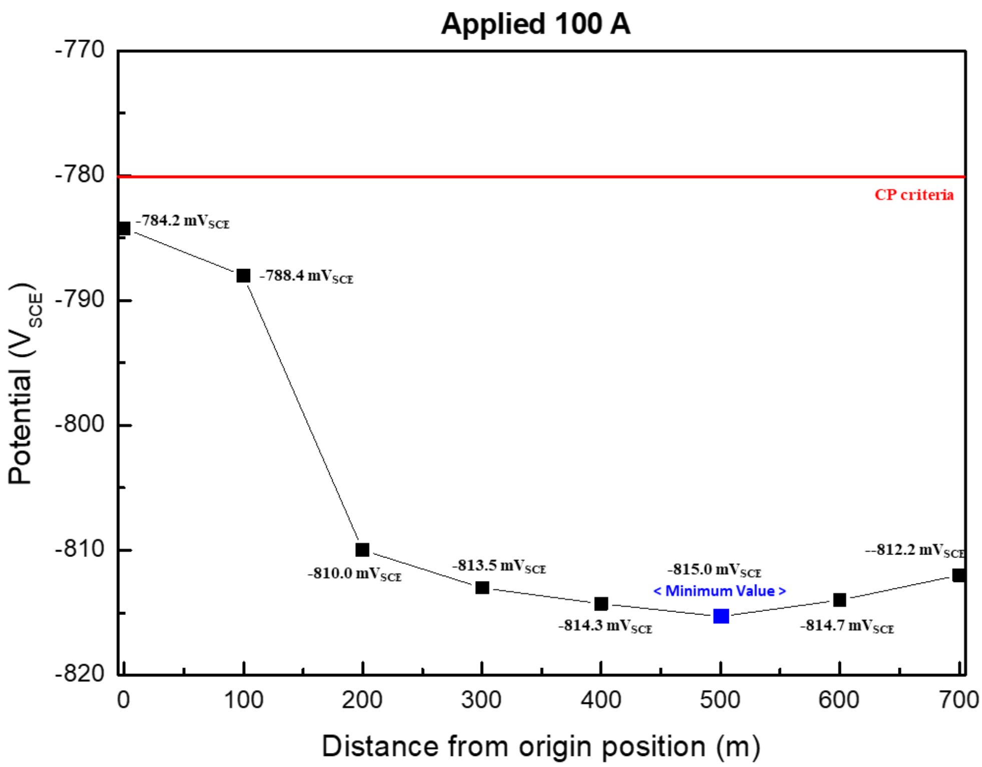

Figure 6. Variation of the maximum CP potential at 100 A according to the anode distance.

For more detailed CP design optimization, the currents 80, 82, 83 and 85 A were applied between 74 and 100 A to the calculated CP condition, which has the distance 400 and 500 m, respectively. Table 2 and Figure 7 show that when the anode was fixed at the origin location, the CP currents at 80, 82, 83, and 85 A did not satisfy the CP criteria. Like the tendency of the results at 74 and 100 A, as the anode distance increased to 500 m, the maximum CP potential was reduced. Consequently, the optimized CP design could be achieved at the anode location of 400 m, with CP current of 83 A which has -780.8

mV_{SCE}. This study shows the significance of anode location and distribution to structure in CP design. Additionally, the computational analysis should be conducted to obtain more stable and reliable CP design in the real field.

Table 2. Variation of the maximum CP potential according to the applied CP current and anode distance.

Applied CP current (A)	Maximum CP potential (mV_{SCE})		
	0 m	400 m	500 m
74	-751	-769	-769
80	-756	-771	-772
82	-757	-776	-778
83	-757	-780	-781
85	-763	-786	-786
100	-784	-814	-815

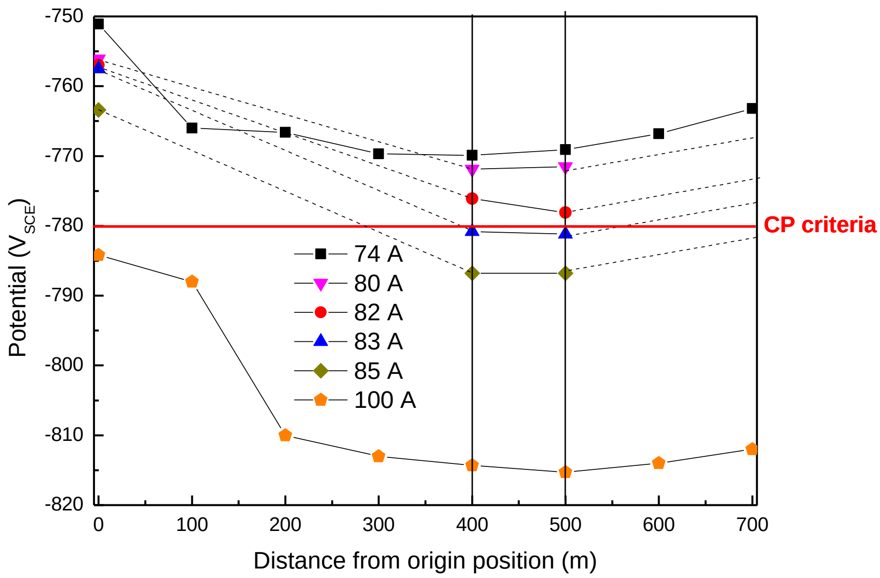

Figure 7. Variation of maximum CP potential from 74 to 100 A according to the anode distance.

5. CONCLUSIONS

In this study, the location of anodes was heavily considered to obtain a reliable CP design method for an existing river-crossing DH pipeline of the Han River. Computational analysis was performed to verify and optimize the CP design. According to the analysis results, the following conclusions were drawn:

- In the case of 74 A, which is the current calculated by theoretical method, the maximum CP potential showed a decreasing tendency according to the anode distance until 400 m; however, it did not satisfy the CP criteria for all the anode locations.
- The 100 A case, which is the optimized CP current without anode movement from the previous study showed a similar tendency. All of the results satisfied the CP criteria, and the lowest potential was observed at 500 m.
- From both results, it can be concluded that the optimized distance of anode is between 400 and 500 m within the range 74 to 100 A. Consequently, the optimized CP design can be achieved at the anode location of 400 m with CP current of 83 A.
- This study shows the significance of anode location and distribution to structure in CP design. Additionally, the computational analysis should be conducted to obtain more stable and reliable CP design in the real field.

AUTHOR CONTRIBUTIONS

Conceptualization, MSH; Methodology, MSH; Software, MSH; Validation, MSH and JGK; Formal analysis, MSH; Investigation, MSH; Resources, MSH; Data curation, MSH; Writing—original draft preparation, MSH; Writing—review and editing, MSH and JGK; Visualization, MSH; Supervision, JGK; Project administration, MSH and JGK.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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