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## HALF-CELL POTENTIAL MEASUREMENTS TO ASSESS CORROSION RISK OF REINFORCEMENT STEELS IN A PC BRIDGE

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### Abstract

Half-cell potential measurements are simple, inexpensive and virtually non-destructive techniques to assess the corrosion risk of steels in concrete. This paper reports a practical application of half-cell potential measurements on an existing prestressed concrete (PC) bridge near the coastline in Japan. The PC bridge shows no signs of deterioration on the concrete surface.

The measured values of the half-cell potential fluctuate due to several factors: the temperature, the type of reference electrode, and the pre-wetting time. However, the negative potential area on the equipotential contour map corresponds to high chloride content and localized corrosion. The numerical criteria disagree with the corrosion condition of steels. Hence, the equipotential contour map is a more reliable tool for detecting localized corrosion than the numerical criteria, even if there are no signs of deterioration due to corrosion on the concrete surface.

### 1. INTRODUCTION

Corrosion of steels in concrete is a global problem for concrete structures. In Japan, many concrete bridges along the coastline have suffered corrosion due to chloride ingress from sea water. When steels corrode, there are usually signs of deterioration on the concrete surface such as rusting, cracking and spalling. However, once these signs of corrosion appear, it may be too late to prevent the advance of deterioration by repair works. The past research [1] shows that the life cycle cost (LCC) of prestressed concrete (PC) bridges that have deteriorated due to chloride attack is 1.5 times the initial construction cost, since the start of repair works is delayed. In addition to the increasing LCC, more than 50% of concrete structures near the coastline have again exhibited deterioration in the repaired area within ten years after repair works have been conducted. These facts suggest that repair works should be

started before signs of corrosion on the concrete surface are detected. Moreover, the corrosion risk of steels in concrete should be assessed at regular intervals.

Half-cell potential measurements are simple, inexpensive and virtually non-destructive techniques to assess the corrosion risk of steels in concrete. These measurements can be used to estimate the corrosion risk of steels even if there are no signs of corrosion on the concrete surface, which is a significant advantage for inspecting existing concrete structures. However, different organizations have different recommendations on half-cell potential measurements. ASTM C 876 [2] suggests numerical criteria for assessing the corrosion risk of steels based on a survey of concrete bridge decks [3]. Meanwhile, RILEM TC 153-EMC [4] suggests that numerical criteria, such as ASTM C 876, lead to misinterpretation because the measured values of the potential fluctuate due to various factors. RILEM also recommends focusing on the potential gradient or difference rather than the measured value of the potential.

This paper reports a practical application of half-cell potential measurements on an existing PC bridge near the coastline in Japan. The PC bridge has been used in a severe chloride environment for over 30 years, but there are no signs of corrosion on the concrete surface. The results of half-cell potential measurements are compared with those of other destructive tests, such as chloride analysis and visual inspection of steels. Moreover, the fluctuation of measured values due to several factors, including the temperature, the type of reference electrode, and the pre-wetting time, is examined using the data from the survey on the PC bridge. Based on these findings, the interpretation of half-cell potential measurements and their use for assessing the corrosion risk of steels are discussed.

## 2. EXPERIMENTAL

### 2.1 Details of the PC bridge

Figure 1 shows the appearance of the PC bridge. It was built in 1975, and has a span length of 25 m. Much airborne salt must have been present during the in-service period because the bridge locates within 200 m from the coastline. The second beam from the sea side was selected for the experiment. It showed no signs of corrosion on the concrete surface and had never been repaired. However, corrosion was highly likely to have started behind the concrete cover since the PC bridge has been used in the severe chloride environment for over 35 years. A visual inspection cannot provide adequate information on the corrosion risk of steels embedded in concrete.



Figure 1: Appearance of PC bridge

## 2.2 Measurement procedure of half-cell potential

The half-cell potential was measured as follows. First, the electrical continuity of web reinforcements was checked at three distant points: PC1, PC2 and PC3, which were selected at random on the web. The concrete cover was removed and web reinforcements were exposed. Then, the potential differences among the three points were measured with a voltmeter and all measured values were less than 1 mV. Thus, the electrical continuity was verified. Additionally, these windows were used for the connection between the web reinforcement and the high-impedance voltmeter. Second, tap water was sprayed on the concrete surface for the pre-wetting in order to reduce the fluctuation of the measured values. Third, the reference electrode and the web reinforcement were connected to a high-impedance voltmeter with lead wires. After the pre-wetting and the connection of devices, the reference electrode was placed on the concrete surface. The measured values of the half-cell potential were recorded at regular intervals. The measurement points were spaced 300 mm apart in the direction of the bridge axis, which corresponded with the spacing of the web reinforcement. Hence, the measurement points were located immediately above the web reinforcements. This was because the corrosion risk due to the airborne salt was likely to be higher for the web reinforcement located nearest to the concrete surface than other steels. Figure 2 shows the measurement points of the half-cell potential on the beam. Nine measurement points were arranged on each cross section: two on the web, four on the lower flange and one on the bottom. These measurement points were set on 74 cross sections on the beam. Figure 3 shows the configuration of half-cell potential measurements.

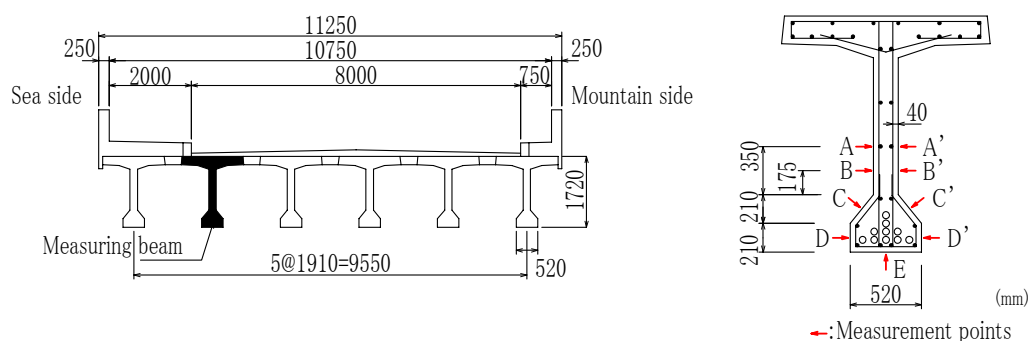


Figure 2: Measurement points of half-cell potential on the beam



Figure 3: Situation of half-cell potential measurements

The experiment was conducted in order to clarify the fluctuation of the half-cell potential due to various factors: the temperature, the type of reference electrode, and the pre-wetting time. To do this, the half-cell potential was measured in summer and winter. The temperature was approximately 30°C in summer and 5°C in winter. Three types of reference electrode were used for the measurement: a silver/silver chloride electrode, a lead electrode and a copper/copper sulphate electrode. Figure 4 shows these reference electrodes. Each measured value was converted to the potential of the copper/copper sulphate electrode at 25°C using the equations shown in Table 1 [5]. Moreover, the pre-wetting time was extended from 30 minutes to 150 minutes by 60 minutes to increase the moisture content of the concrete.

The results of half-cell potential measurements were plotted on an equipotential contour map for visual interpretation.

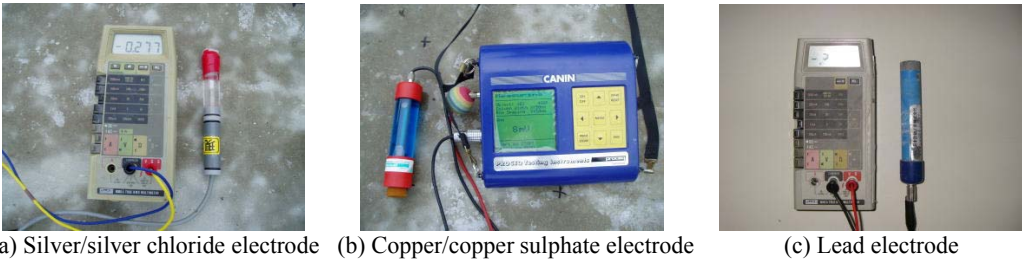


Figure 4: Reference electrodes

Table 1: Conversion equation of half-cell potential

| Type of reference electrode      | Conversion equation<br>(Potential of copper/copper sulphate electrode at 25°C) |
|----------------------------------|--------------------------------------------------------------------------------|
| Copper/copper sulphate electrode | $0 + 0.9 \times (t - 25)$                                                      |
| Silver/silver chloride electrode | $-74 - 0.66 \times (t - 25)$                                                   |
| Lead electrode                   | $-799 + 0.24 \times (t - 25)$                                                  |

t: temperature (°C) at the time of measurement

**2.3 Chloride content and corrosion state of steels**

The results of half-cell potential measurements were compared with those of the chloride analysis and the corrosion state of steels. The tests of the chloride content and the visual inspection of steels were conducted before and after measuring the half-cell potential. Before measuring the half-cell potential, in addition to checking the electrical continuity, a core sample, 25 mm in diameter, was taken for chloride analysis and the corrosion state of steels was inspected at three points: PC1, PC2, and PC3. Meanwhile, after measuring the half-cell potential, the negative potential area on the equipotential contour map was detected and the chloride content at the web reinforcement was measured at two points: PC4 and PC5. Moreover, the visual inspection of web reinforcements was conducted at the most negative

potential area: PC5. The relationship between the numerical criteria and the corrosion state was also discussed based on the experimental results.

### 3. RESULTS AND DISCUSSION

#### 3.1 Half-cell potential, chloride content and corrosion state of steels

Figure 5 shows the results of half-cell potential measurements and the chloride analysis. The results of half-cell potential measurements are represented as an equipotential contour map for each season, using different colors for each 50 mV. The measurement was conducted with the silver/silver chloride electrode after 30 minutes of the pre-wetting. The depth of carbonation by spraying phenolphthalein solution was approximately 9 mm. The thickness of concrete cover at the web reinforcement was 40 mm. Thus, it is reasonable to assume that carbonation has no relationship with corrosion. The measured values of the moisture content on the concrete surface were between 5% and 8% after the pre-wetting. The compressive strength of concrete obtained by compression tests of the core sample taken for the chloride analysis was approximately 45 MPa.

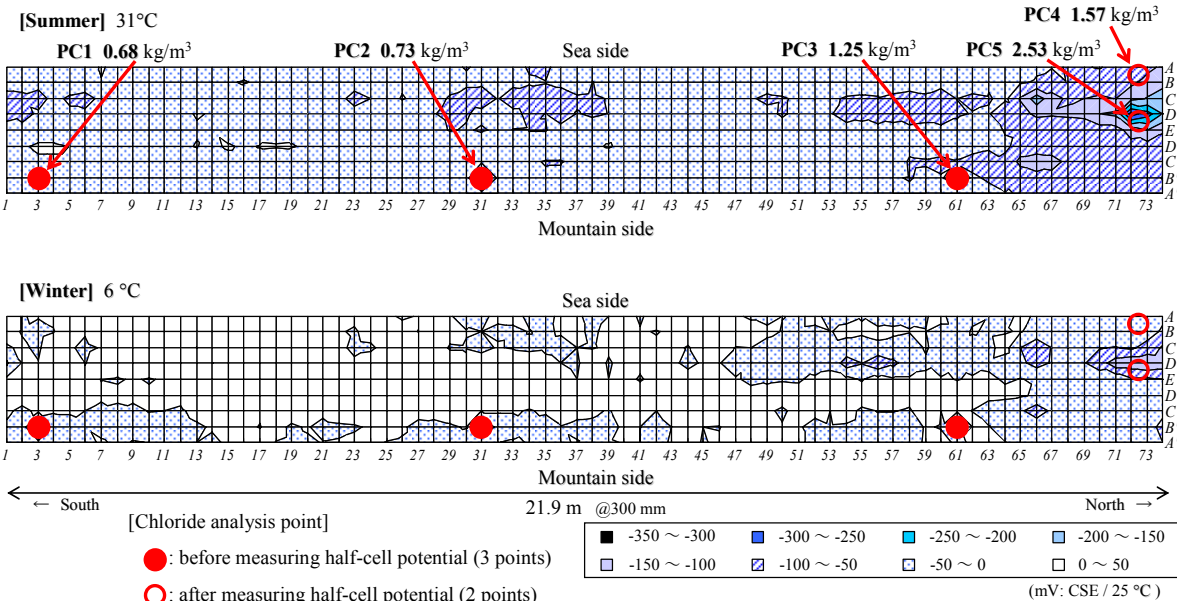


Figure 5: Equipotential contour maps of PC bridge in summer and winter

The measured values of the half-cell potential in summer were more negative than those in winter. The most negative potential was obtained around the measurement points of 73 on the measurement line of D: -320 mV in summer and -145 mV in winter. This area was located on the sea side of the beam, where much airborne salt was present from the sea water. Comparing the results of the chloride analysis, the chloride content at PC5 was highest among the five points PC1 to PC5. Figure 6 shows the relationship between the half-cell potential and the chloride content at the web reinforcement. The half-cell potential shifted depending on the season, but it was obvious that the negative potential was measured where the chloride content at the web reinforcement was high.



Figure 7 shows the corrosion state of web reinforcements at four points: PC1, PC2, PC3 and PC5. Corrosion was found only at PC5, where the most negative potential was measured. Hence, the negative potential area on the equipotential contour map should be a good indicator to detect points with high chloride content and localized corrosion even if there are no signs of corrosion on the concrete surface.

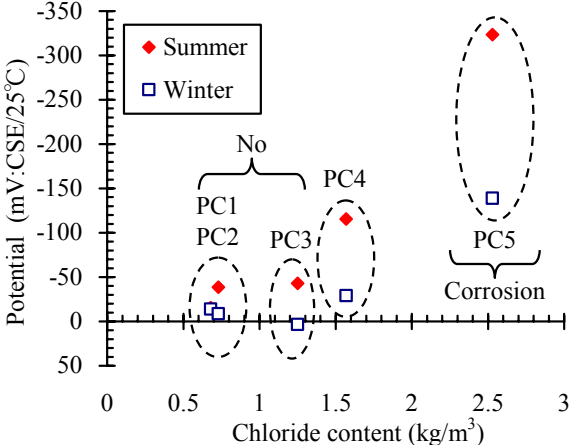


Figure 6: Half-cell potential and chloride content



(a) PC1 (b) PC2 (c) PC3 (d) PC5  
 \* PC1, PC2, PC3: No corrosion, \*\* PC5: Corrosion

Figure 7: Corrosion state of web reinforcements

**3.2 Temperature and half-cell potential**

As shown in Figure 5, there is a difference of the half-cell potential between summer and winter. Most of the measured values were between -50 mV and 0 mV in summer, and between 0 mV and 50 mV in winter. Figure 8 compares the half-cell potential in summer and winter, deriving the measured values on the measurement line of D from Figure 5. The half-cell potential in summer was shifted by approximately 40 mV to more negative values than in winter. This shift was induced throughout the beam, but the gradient of the half-cell potential remained at the same pattern. These facts imply that the half-cell potential fluctuated due to the change of corrosive environment in concrete depending on the temperature. The corrosive environment became more severe as the temperature increased. Meanwhile, the difference of

the gradient became clear in summer, which was helpful to detect the negative potential area on the equipotential contour map.

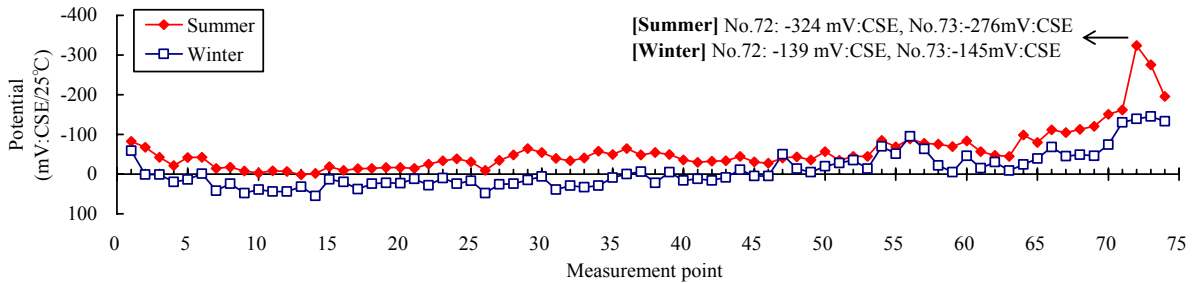


Figure 8: Half-cell potential in summer and winter

### 3.3 Type of reference electrode and half-cell potential

Figure 9 shows the half-cell potential for three types of reference electrode: the silver/silver chloride electrode, the lead electrode and the copper/copper sulphate electrode. The measurement was conducted after 30 minutes of the pre-wetting on the measurement line of D in summer. The average difference of the measured values among the three reference electrodes was approximately 70 mV on the whole of the beam. The negative potential was obtained in the following order: the lead electrode, the copper/copper sulphate electrode and the silver/silver chloride electrode. However, the potential gradient with three different reference electrodes was almost equal. Additionally, the difference of the measured values decreased around the measurement points of 74 and 75, where the most negative potential was obtained. Thus, it is unlikely to lead to different interpretations depending on the type of reference electrode.

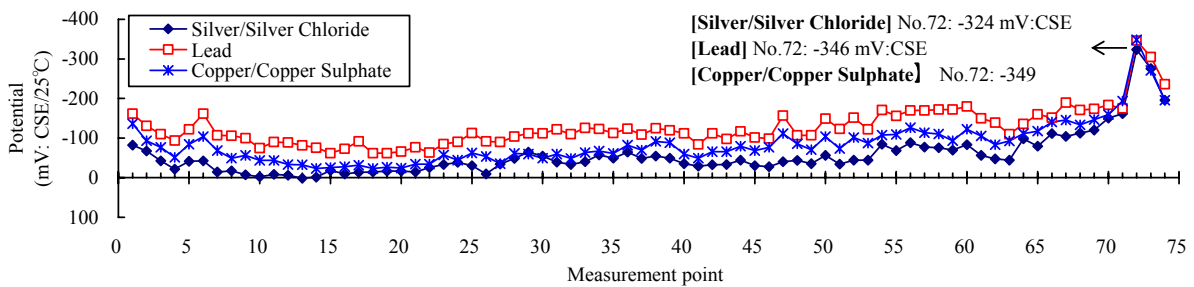


Figure 9: Half-cell potential with three types of reference electrode

### 3.4 Pre-wetting time and half-cell potential

Figure 10 shows the half-cell potential for different pre-wetting times. The pre-wetting time was 30, 90 and 150 minutes. The measurement was conducted on the measurement line of D with the copper/copper sulphate electrode in summer. The half-cell potential became more negative with increase of pre-wetting time. However, the potential gradient remained at the same pattern again; the most negative potential was obtained at the measurement points of 74 and 75. Hence, the length of the pre-wetting time also affected the measured values of the half-cell potential, but the potential gradient was not changed.

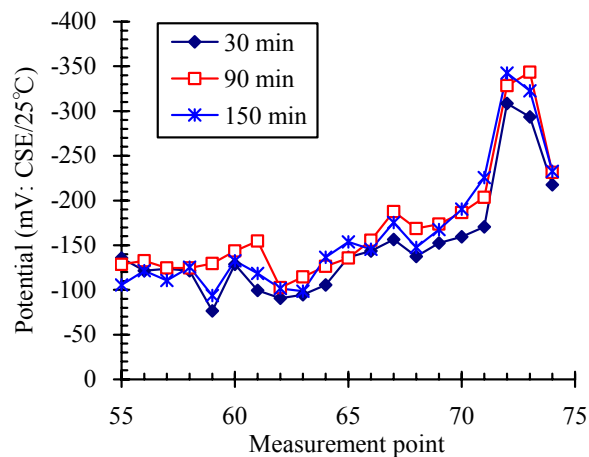


Figure 10: Half-cell potential for different pre-wetting times

### 3.5 Interpretation of half-cell potential

The numerical criteria recommended in ASTM C 879 are the most widespread standard used to assess the corrosion risk of steels in concrete. In the current research work, all measured values were more positive than  $-350$  mV, which is the numerical boundary of a greater-than-90% probability of corrosion in ASTM C 879. Hence, it seems reasonable to consider that the corrosion risk is low for this PC bridge. However, the visual inspection of web reinforcements showed that there was localized corrosion where the most negative potential was obtained regardless of fluctuations due to the temperature, the type of reference electrode, and the pre-wetting time. This fact reveals that the numerical criteria do not necessarily agree with the corrosion state of steels in concrete.

This disagreement is probably due to the fluctuation of the half-cell potential and the effect of macro-cell corrosion. As previously mentioned, various factors cause the half-cell potential to fluctuate. Additionally, macro-cell corrosion also causes the half-cell potential to fluctuate due to the polarization. The potential at PC5 may have been shifted by the polarization because the web reinforcement at PC5 is the site of localized corrosion, which induces macro-cell corrosion with other sound web reinforcements. Hence, the potential at PC5 became more positive than  $-350$  mV even though the web reinforcement was located in a severely corrosive environment. Based on these facts, it should be stressed that the equipotential contour map is a better tool for assessing the corrosion risk of steels on existing PC bridges. This finding is similar to that of past research works on concrete bridge decks [6], [7].

Additionally, reliable information is indispensable to assess the condition of concrete structures. In the current research, the measurement points were placed at 300 mm according to the spacing of the web reinforcement. If the measurement points had been spaced further than 300 mm apart, the half-cell potential at measurement points 74 and 75 may not have been obtained, in which case the negative potential area and the localized corrosion might have been overlooked. Hence, the measurement points should be placed according to the spacing of the steel.



#### 4. CONCLUSIONS

Based on the current research work, the following conclusions can be drawn regarding the application of half-cell potential measurement to assess the corrosion risk of existing concrete structures.

- The most negative potential area on the equipotential contour map corresponds to the point with high chloride content and localized corrosion. The potential gradient is a good indicator to select the position for further destructive tests if there are no signs of corrosion on the concrete surface.
- The measured values of the half-cell potential could fluctuate due to various factors, such as the temperature, the type of reference electrode, and the pre-wetting time. However, the potential gradient remains at the same pattern on the whole of the structure.
- The numerical criteria are not particularly suitable for assessing the corrosion risk of existing concrete structures. The equipotential contour map is a more reliable tool for detecting localized corrosion and deciding the position for further destructive tests.

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#### REFERENCES

- [1] Watanabe, H. and Koga, H., “General Information on Deterioration of Existing Concrete Structures and Recent Research Topics in PWRI,” Proceedings of the International Workshop on Life Cycle Management of Coastal Concrete Structures, Nagaoka, Japan (2006), 43-54.
- [2] ASTM C 876-91 (Reapproved 1999), “Standard Test Method for Half-cell Potentials of Uncoated Reinforcing Steel in Concrete,” Annual Book of ASTM Standards, 03.02 (2006), 11-16.
- [3] Stratfull, R. F., Jurkovich, and W. J., Spellman, D. L., “Corrosion Testing of Bridge Decks,” Highway Research Record 539, Washington, D. C., Transportation Research Board (1975).
- [4] RILEM TC 154-EMC, “Electrochemical Techniques for Measuring Metallic Corrosion” Recommendations, “Half-cell potential measurements – Potential mapping on reinforced concrete structures,” *Materials and Structures*. 36 August - September (2003), 461-471.
- [5] JSCE-E 601-2000, “Test Method for Half-cell Potentials of Uncoated Rebars in Concrete Structures,” Standard Specifications for Concrete Structures – 2002, Test Methods and Specifications, Japan Society of Civil Engineers (2002) (in Japanese).
- [6] Elsener, B. and Bohni, H., “Potential Mapping and Corrosion of Steel in Concrete,” in “Corrosion Rates of Steel in Concrete,” ASTM STP 1065, N.S. Berke, V. Chaker, D. Whiting eds. American Society for Testing and Materials, Philadelphia (1990), 143-156.
- [7] Clemena, G. G., “Benefits of Measuring Half-cell Potentials and Rebar Corrosion Rates in Condition Surveys of Concrete Bridge Decks,” Virginia Transportation Research Council (1992).