# Evaluation of steel corrosion by numerical analysis

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## Abstract

Recently, various non-destructive and numerical methods have been used and many cases of steel corrosion are examined. For example, methods of evaluating corrosion through various numerical methods and evaluating macro-cell corrosion and micro-cell corrosion using measurements have been proposed. However, there are few reports on estimating of corrosion loss with distinguishing the macro-cell and micro-cell corrosion and with resembling an actuality phenomenon.

In this study, for distinguishing between macro-cell and micro-cell corrosion, electrochemical non-destructive methods and numerical methods are used to measure steel plate corrosion induced by chloride ions.

**Key words :** electrochemical method, steel corrosion, macro-cell, micro-cell, numerical analysis

## 1. Outline of Numerical Analysis

### 1. 1 Corrosion Cases

Experimental conditions and items were already described in report [1]. Thus, these are omitted in here. Corrosion cases using the measurement and analysis results are shown in Table 1. Corrosion quantity (W ) of the steel plate by calculating from the measurement and analysis was estimated by the following formula:

$$W\,(\mathrm{g/cm^2}) = \frac{a}{c}\int I_{corr}dt = \frac{a}{c}\int K\ (1/R_p)\ dt \qquad (1)$$

where, *Icorr*: corrosion current density (A/cm$^2$); *K*: proportional constant (V); *Rp*: polarization resistance (Ω·cm$^2$); *a*: value of at. wt. of iron divided by valency 2 (27.9g); and *c*: the Faraday constant (96,500C)

The corrosion cases examine using specimens L1 and S1, as shown in **Table 1**, are classified as follows:

L1: Corrosion estimated from macro-cell analysis (L1-MA: **1**) and corrosion estimated from polarization resistance (L1-MA: **2**)

S1: Corrosion estimated from macro-cell analysis with leads connecting the steel plates (S1-MA: **3**) corrosion estimated from the polarization resistance of each point (S1-MA-mi: **4**), and micro-cell corrosion estimated from the polarization resistance the steel plates are disconnected (S1-mi: **5**)

Table 1 Corrosion cases for specimens L1 and S1

| | L1: Large steel plate (Exposure surface:15 × 1810 mm) | S1: Short steel plate (Exposure surface: 15 × 95 mm × 18+10 mm) |
|---|---|---|
| Macro-cell corrosion of continuous steel plate | L1-MA | S1-MA |
| Corrosion of continuous steel plate | L1- MA-mi | S1- MA-mi |
| Micro-cell corrosion of separated steel plate | ―――――――― | S1- mi |

## 1. 2 Macro-cell corrosion

Generally, the distribution of two-dimensional potential (u) in concrete determined using Laplace's equation, as (2) below.

$$\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}=0 \qquad (2)$$

The equation can be solved by calculus of finite difference [2] or a finite-element method [3]. The following conditions were used to analyze Laplace's equation and the finite difference method was applied.

(a) An approximate quantic curve was fitted to the measured potential at the fixed intervals (L1: 50 mm; S1: 95 mm), and the potential obtained for every 2.5 mm interval for analysis using the finite difference method.

(b) It was supposed that the concrete surface potential was the steel plate surface potential in (a) because the thickness of concrete was thin as 20 mm [3]. As the boundary condition, it is supposed that the concrete surface and both ends had a potential equal to the neighbor potential at the closest internal point. The number of axial analysis node was 725 (L1) and 689 (S1), so the total node count in the analysis was (steel plate axial direction) x 8 (the direction of concrete depth) = 5,800 (L1) and 5,512 (S1). Calculations were iterated until the difference between each node potential and the previous potential was equal or less than 0.0001 mV.

(c) The inward/outward flow of electric current and the corrosion current density at the steel plate surface were obtained from the potential distribution in (b), the concrete resistance as resistivity, and the polarization resistance of each measurement point.

There are two main aims for the numerical analysis:

(1) comparison of macro-cell corrosion analysis using half-cell potential, concrete resistance and polarization resistance

(2) estimation of corrosion loss and relation of macro-cell corrosion between analysis, electric-current and polarization resistance

# 2. Analytical Results

## 2. 1 Distribution of potential and current by macro-cell analysis

The steel plate surface potential is shown in **Fig.1**. The potential distribution for macro-cell corrosion analysis was obtained from regressing the approximate quantic curve to the points of measurement and non-meas. as described on (a) in paragraph **1.2**. Various formula were used for the regression curve, and the correlation of the 4th quantic was the highest with a coefficient of correlation "$R^2$" of about 0.99. The measured potential at 10 mm intervals was compared with the value from the approximate expression, but there were no problems in the regression curve.

The current distribution on the steel plate surface, as obtained in the analysis, is shown in **Fig.2**. The inset figure is a magnification of the transverse direction in the vicinity of the salt cell of L1 and S1; it can be seen that the current calculated from the potential and concrete resistance is bigger than that when polarization resistance is considered. However, this difference was on the appearance and no conspicuous difference was found by integrated value which is equivalent to the anode current in the paragraphs that follow. From these results, it is considered that the difference in current between the potential/concrete-resistance and the potential /concrete-resistance/ polarization-resistance calculations was not large, and that there was almost no difference in the analysis of corrosion current and macro-cell corrosion quantity.

## 2. 2 Evaluation of measurement/analysis values of macro-cell corrosion for S1 (S1-MA)

The integrated anode current for steel plate (Sc), which is the one with the saltwater cell, as determined by the analysis is shown in **Table 2**. Two cases were analyzed; the half-cell potential and the concrete resistance; and the half-cell potential, the concrete resistance, and polarization resistance. In both cases, it was assumed that the concrete resistance was uniform over the specimen and that current could be calculated using the maximum, minimum, and average concrete resistance.

The current values obtained using only the potential and concrete resistance are several percent higher than those where polarization resistance is also considered, but the difference was not large. This means that the difference in current distribution, as calculated in each case, was observable but does not significantly affect the analysis results. The anode current is largest when the minimum value of concrete resistance is used, and it decreases according in the case of the average or maximum concrete resistance. It was found that anode current distributed mostly in 0-105 mm length of Sc plate though anode current in a little was out 0-105 mm length. From these results, the outflow current would be from only Sc plate which is the one with the salt water cell.

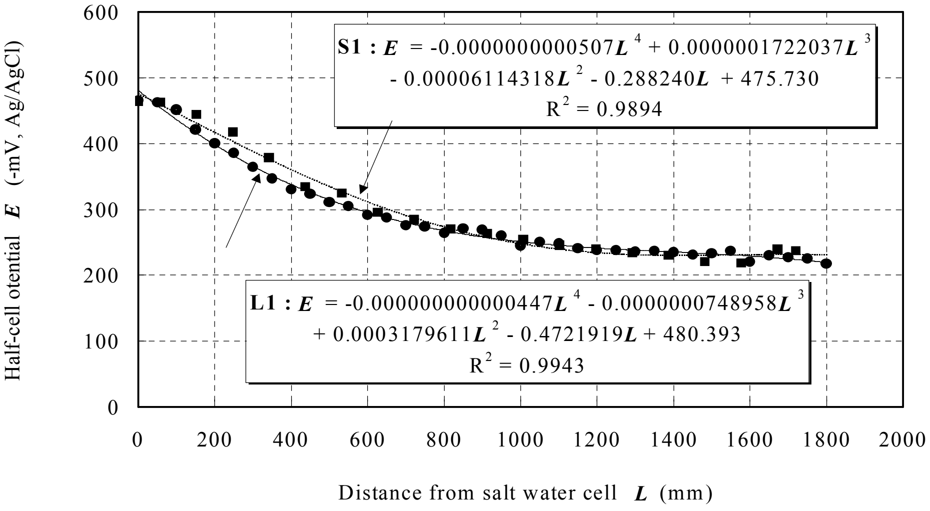


**Fig. 1 Half-cell potential distribution and application of quantic curve**

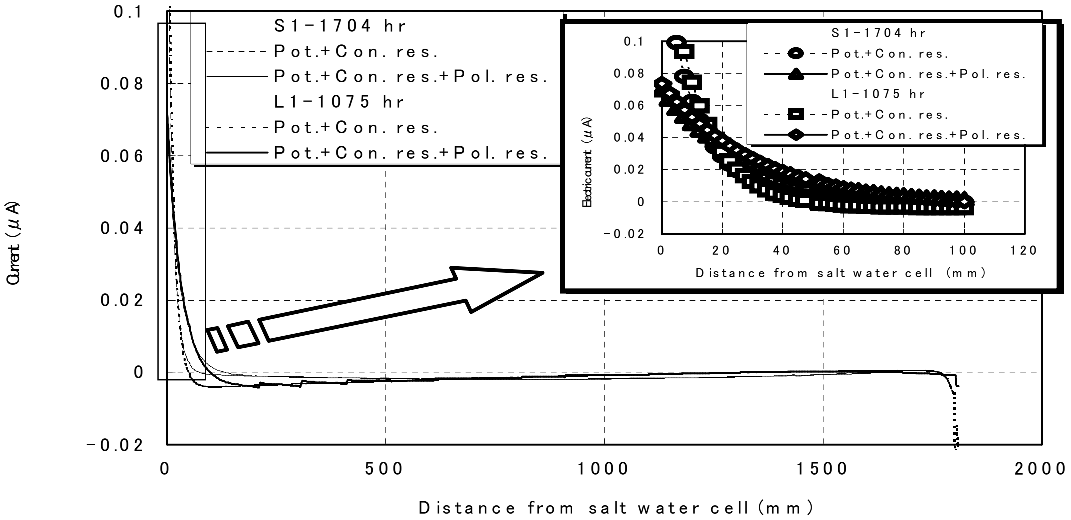


Fig. 2 Vertical component of current for certain cases

**Table 2 Anode current by numerical analysis**

**(Accumulated value of vertical component of current passing through vertical/horizontal section of 0-2.5/0-105 mm of Sc steel plate)**

| Period after supplying salt water (hr) | Analysis using pot. and con. | | | Analysis using pot., con. and pol. | | |
|---|---|---|---|---|---|---|
| | Current 0-2.5 mm section above steel plate (μA) | | | Current 0-2.5 mm section above steel plate (μA) | | |
| | Rc : max. | Rc : min. | Rc : ave. | Rc : max. | Rc : min. | Rc : ave. |
| 1608 | 0.3267 | 1.1189 | 0.5890 | 0.3261 | 1.0731 | 0.5839 |
| 1704 | 0.4866 | 1.6764 | 0.8332 | 0.4804 | 1.5899 | 0.8105 |
| 1851 | 0.4974 | 1.8982 | 0.8143 | 0.4897 | 1.8524 | 0.8006 |
| 2208 | 0.4669 | 1.7667 | 0.8089 | 0.4657 | 1.7495 | 0.8049 |
| 2520 | 0.5640 | 2.2234 | 0.8884 | 0.5590 | 2.1940 | 0.8796 |
| 3192 | 0.3957 | 2.0584 | 0.7381 | 0.3955 | 2.0507 | 0.7375 |

Note pot. : potential, con. : concrete resistance, pol. : polarization resistance
Rc : concrete resistance, max. : maximum, min. : minimum, ave. : average

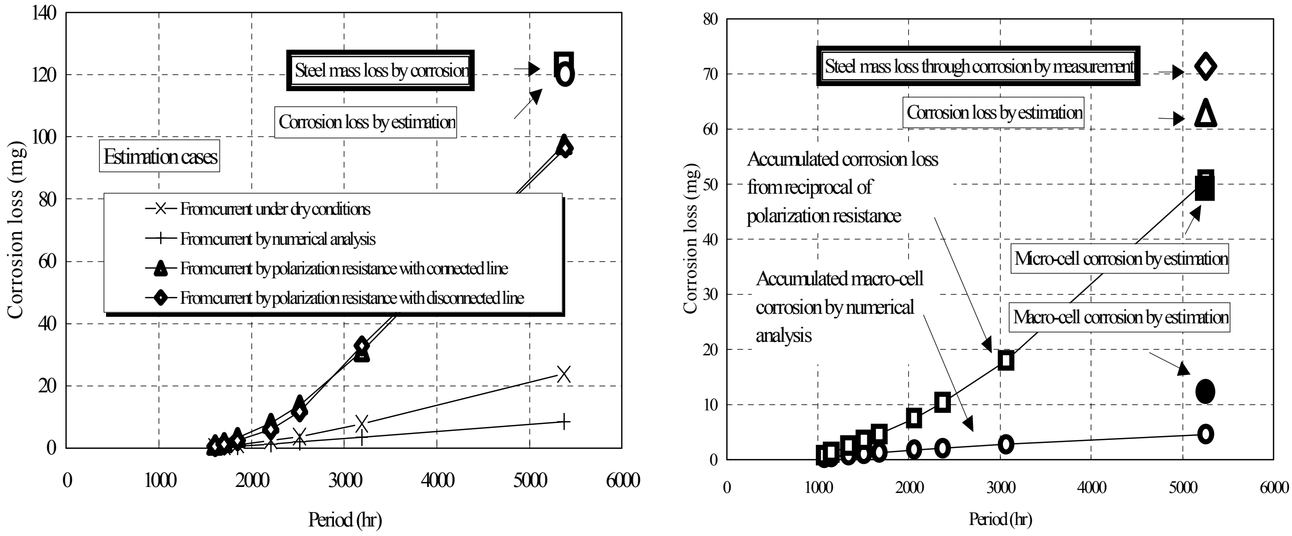
## 2. 3 Estimation of corrosion quantity and mass loss by corrosion

The final process is to calculate the total amount of corrosion from the accumulated corrosion amount analyzed under each condition for S1 and L1. The relationship between the change in corrosion quantity and mass loss are shown in **Fig. 3** (a) and (b). The analysis result and the measurement of corrosion mass loss was limited to the region of the plate with a salt water cell on both S1 and L1 (the length of L1 is equal to the length of Sc part of S1). It was expected that the corrosion mass loss would be affected by loss of resin coating and the influence of mortar adhesion, but no influences were seen.

When the plates in S1 were connected in this model test, the corrosion quantity determined from the reciprocal of polarization resistance was a little larger than during temporary disconnection of the plates, but the difference was not very great. In fact, the corrosion loss obtained with disconnection is equal to or more than 90 % of that obtained from polarization resistance in the connection state, so the difference in corrosion quantity is several percent at most.

In **Fig.3 (a)**, it is supposed that the corrosion loss of S1 with disconnection is the micro-cell corrosion, whereas the corrosion loss obtained from the current between the steel plates under dry conditions is the macro-cell corrosion quantity. The total amount of corrosion was calculated to be 120.2 mg, a value near the actual corrosion loss of 123.3 mg. On the other hand, in **Fig. 3 (b)**, the accumulation corrosion loss obtained from the reciprocal of the polarization resistance on the steel plate near the salt water cell of L1 was 50.7 mg. From the relation between connected and disconnected time for S1, this 50.2 mg is converted into the micro-cell corrosion. The macro-cell corrosion loss obtained by analysis of L1 was calculated from the ratio explained below. The analysis macro-cell corrosion of L1 was multiplied by the ratio of macro-cell corrosion quantity of S1 between measurement under dry condition and analysis. Based on this result, the total corrosion loss by calculation is 63.1 mg, and this is about 88% of the actual corrosion loss of 72.1 mg.

Though the estimate value is lower than the actual value, the calculation can be considered suitable for evaluating the corrosion of continuous steel material using something like the S1 model (with connected and temporary disconnected short steel plates). In particular, to specify the corrosion accurately, it is possible to estimate the total corrosion loss by taking the macro-cell corrosion from analysis and the micro-cell corrosion obtained from the polarization resistance near the corroded area. This means that, in order to examine steel corrosion in concrete structures, it will be necessary to go through the following steps:



**(a) Corrosion loss by estimation and steel mass loss by corrosion (S1)**

**(b) Corrosion loss by estimation and steel mass loss by corrosion (L1)**

**Fig. 3 Corrosion loss by estimation and steel mass loss by corrosion (S1 and L1)**

## 3. Conclusion

This estimation means that, in order to examine steel corrosion in concrete structures, it will be necessary to go through the following steps:

(1) obtain the current distribution due to macro-cell corrosion from measurements such as the half-cell potential, the polarization resistance, and the concrete resistance, the definite boundaries of the anode and cathode regions, and an estimate of macro-cell corrosion loss

(2) obtain an estimate of micro-cell corrosion loss from the reciprocal of the polarization resistance in the anode area, which is obtained from (1)

(3) estimate the total corrosion loss from the relation between (1) and (2)

On the other hand, though the rate of micro-cell corrosion is large in the model test, this may result from the indoor dry environment to which the specimen was exposed. Thus, it can be assumed that there was little development of macro-cell corrosion. In work to follow, it will be necessary to examine the repeatability of these macro-cell corrosion analysis results and the choice of coefficient K for determining corrosion from the reciprocal of polarization resistance. Further, it will be necessary to carry out more detailed examinations, such as experiments under various levels of salinity including a case where the main loss is macro-cell corrosion.

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