Numerical and experimental development of gradient potential measurement for corrosion detection of reinforced concrete slab

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Abstract:
Half-cell potential mapping is commonly used to detect corrosion risks in Civil Engineering structures. This method uses a reference electrode measuring potential difference with a connection to the reinforcement. There are two major drawbacks in the use of this method: the electrical connection to the rebar and its electrical continuity. A new method is proposed to overcome these disadvantages. Instead of using electrical connection to rebar, a second reference electrode is used, also positioned on the surface. These two electrodes result in electrical potential gradient on the concrete surface.

By performing experiments and modeling, the new method is tested. For experimental work, two reinforced concrete slabs (3x3x0.15 meter sized) were casted to be close to actual structural conditions. The first slab includes rebar where the cover is fixed, while it is variable in the second slab. Then corroded areas controlled size are created through a specific migration chlorides device. For modelling, a parametric study using a finite element model is performed. This model allows the study of several parameters such as resistivity, corroded area size, concrete cover, and also the measurement process.

It is the analysis of the corrosion current, as well as potential mapping that allows the correlation between the experimental and modeling results. Discussion of both results concludes feasibility of this method and confirms its benefits compared to half-cell potential mapping.

Keywords: Non-destructive method; modeling; potential; concrete.
**Introduction**

The main factor of reinforced concrete building destruction is the corrosion of reinforcement bars. It is possible to observe in a world-wide scale because of structures ageing. That’s why detection and diagnostic are a major challenge in order to extend the structure durability. Non Destructive Techniques (NDT) are useful in risk area detections: they give quick and less expensive information than intrusive methods. Carry out early enough and regularly the structure rehabilitation cost decreases, therefore their development is crucial.

Electrochemical NDT, like half-cell potential mapping [1] and linear polarization resistance [2], are used for the corrosion detection. These methods use an electrical contact to rebar. This connection needs specific materials and time, without this step, the auscultation cost would be reduced. This study aim to develop a NDT which do not needs this electrical link. Therefore, a potential gradient method has been chosen using two reference electrodes [3] and no electrical connection.

To manage the experimental campaign with potential gradient method, a preliminary work was necessary. This work consists in a parametric study using modeling. This study allows understanding the influence of the concrete parameters on the electrical potential in surface of the concrete. Leading parameters are resistivity and the geometry of the system as the coating thickness and steel corroded length. To test the NDT and to be close to actual structural conditions, a concrete slab of 3x3 meter sized was casted. Results of both modelling and experimental work should allow us to conclude in the efficiency of the NDT and model.

**Parametric study**

1. **Model**

Finite Element Methods (FEM) are performed using the physic: “DC Conductive Media” from COMSOL Multiphysics®. Numerical simulations are achieved on square prisms of 1mx1mx20cm concrete for a 10mm rebar diameter and a horizontal spacing of 10cm. It is possible to perform modeling on a quarter of the prism (Figure 1) through the two axial symmetries.

![Figure 1: Prism geometry in reinforced concrete for the modeling of the streamlines distribution](image-url)
In order to determine numerically the current densities in the model, it is necessary to determine the electrical potential at any point of the geometry. Ohm's law links the local electric current density to the conductivity (or resistivity) and the potential gradient (eq.1 and eq.2) under the condition of the charge conservation (eq.3).

\[ j = -\sigma \cdot \nabla \phi_s \]  
\[ j = -\frac{1}{\rho} \cdot \nabla \phi_s \]  
\[ \nabla \cdot j = 0 \]  

(eq.1)  
(eq.2)  
(eq.3)

Our simulations take place in a secondary distribution current between corroded and non-corroded bars, forming a galvanic cell in the system. Electrochemical kinetics are described with Butler-Volmer equations; they are used as boundary conditions, corroded zone being the anode (eq.4) and non-corroded the cathode (eq.5).

\[ j_a = j_{a \text{corr}} \cdot \left[ \exp \left( \log(10) \cdot \frac{(V - E_{corr \text{a}})}{\beta_a} \right) \right] - \exp \left( -\log(10) \cdot \frac{(V - E_{corr \text{a}})}{\beta_c} \right) \]  
\[ j_c = j_{c \text{corr}} \cdot \left[ \exp \left( \log(10) \cdot \frac{(V - E_{corr \text{c}})}{\beta_a} \right) \right] - \exp \left( -\log(10) \cdot \frac{(V - E_{corr \text{c}})}{\beta_c} \right) \]  

(eq.4)  
(eq.5)

Parameters used for the simulation are from [4] obtained with carbonated concrete samples (Table 1).

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Anodic</th>
<th>Cathodic</th>
</tr>
</thead>
<tbody>
<tr>
<td>( j_{\text{corr}} )</td>
<td>Corrosion current density</td>
<td>5.0 ( 10^{-3} ) A/m²</td>
</tr>
<tr>
<td>( \beta_c )</td>
<td>Cathodic Tafel coefficient</td>
<td>0.15 V/dec</td>
</tr>
<tr>
<td>( \beta_a )</td>
<td>Anodic Tafel coefficient</td>
<td>0.09 V/dec</td>
</tr>
<tr>
<td>( E_{\text{corr}} )</td>
<td>Corrosion potential</td>
<td>-0.65 V/ECS</td>
</tr>
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</table>

A mesh of theoretical potential measurement points on the surface of the concrete is drawn by the extracted results. To get closer to a real case of in-situ measurement, position and distance of the meshes will be directly dependent of the measuring steps. The study is about the combination of following parameters:

- Resistivity: \( \rho = 200, 475, 750, \) and 1300Ω.m,
- Coating thickness: \( h = 2, 4 \) and 5cm,
- Corroded length: \( L_{za} = 1 \) cm,
- Measuring steps: \( \text{step} = 2 \) cm.
2. **Parametric study**

**Resistivity**

Resistivity of concrete slab combines numerous physical parameters like: porosity, humidity, and ionic concentrations of the solution pore; resistivity is consequently a crucial factor for the corrosion in concrete.

*Figure 2* identifies the influence of the resistivity on the mapping of electrical potential obtained at the surface. For low resistivity 200 Ohm.m a range from -190mV/SCE for corroded zone to -300mV/SCE above the corroded zone is observed (*Figure 2A*). For high resistivity this scale is between -160mV/SCE and -290mV/SCE (*Figure 2D*). There is an overall decrease in range potential with the decrease of resistivity (*Figure 2A to 1D*). In addition, there is a concentration of highest electro-negative values (<-0.25V/SCE) at the center of the corroded area for a high resistivity, where these values are more diffuse with the lowest resistivity. We can conclude that the increase of ohmic drop due to high resistivity induces current lines containment near the corroded area.

*Figure 3* shows the local corrosion current densities along the upper part of the corroded reinforcement. In the center of the corroded area (x=0.5m), the local current density is higher for low resistivity (in absolute value): \(2.78 \times 10^{-2}\)A/m² for 1300 Ohm.m and \(13.7 \times 10^{-2}\)A/m² for 200 Ohm.m. However, on the non-corroded side, the maximum current density is about \(2.35 \times 10^{-2}\)A/m² for 1300 Ohm.m at x = 0.495m and \(1.20 \times 10^{-2}\)A/m² for 200 Ohm.m. This validates the assumption that the concentration of streamlines is significant near the frontier between corroded and non-corroded areas.
Figure 2: Half-cell potential mapping in function of resistivity (modeling results): A) $\rho = 200$ Ohm.m, B) $\rho = 475$ Ohm.m, C) $\rho = 750$ Ohm.m, D) $\rho = 1300$ Ohm.m.

Figure 3: Current density near the frontier of corroded zone in function of resistivity (modeling results).
Coating Thickness

The distance from the reinforcement to the surface of the concrete has a major impact on the potential values obtained at the surface (Figure 4). In the case of a low coating thickness of 2 cm (Figure 4A), the value range is between -190mV/SCE to -300mV/SCE which is greater than for larger coating thicknesses of 4 and 5 cm (Figure 4B and 4C) -190 to -240V/SCE and -190 to -230V/SCE respectively.

This difference is due to the increasing distance between rebar and measurement zone and thus a removal of the more electronegative isopotentials from the surface of the concrete slab. A strong coating thickness generates a contrast reduction similar to a loss of informations.

Figure 4: Half-cell potential mapping in function of coating thickness (modeling results): A) h=2cm, B) h=4cm, C) h=5cm ; ρ=200 Ohm.m.
Accelerated corrosion method
In order to develop the method of corrosion detection, it was necessary to be able to create quickly some controlled corroded areas. The chosen process was a chloride migration method [5] [6].

1. Method
A hollow cylinder is glued to the surface of the reinforced concrete slab above a rebar intersection (Figure 5). The cylinder is then fills with 300 ml of NaCl solution at a concentration of 20 g/L. Working electrodes become rebar while counter electrode is made of stainless steel. Reference electrode and counter-electrode are positioned inside the cylinder. A generator is set up to connect the plates and counter-electrode in order to output a DC voltage of 20V.

This test is performed on a thin slab of 25x22x7cm dimension (sample B); the reinforcement is composed of reinforcing mesh of three bars spaced out of 10cm. In parallel a second sample (sample A), will be tested in the same conditions without the current injection, being the control sample.

2. Results
After 70 hours of DC voltage, sample A and B were cut in order to measure the chloride penetration depth by spraying a 0.1M silver nitrate solution on to the split section. The formation of a white precipitate composed of silver chloride indicates the presence of chlorides (Figure 6). Specimen A has a maximum chloride penetration depth of 2.2 cm, which is only due to diffusion, but also by capillary absorption. Specimen B has a way greater penetration depth, up to 5.9 cm. This higher result is thanks to ions migration from the counter-electrode to the rebar. Chloride ions are therefore participating to electric current transport in concrete samples. This is confirmed by the fact that 13.2% of chloride ions located in the cylinder are consumed for the sample A (control sample); and 49.2% for the sample B (migration test).
Figure 6: Pictures of sample A (diffusion/absorption) and B (migration/diffusion/absorption) after the test, split and AgNO₃ spraying.

The autopsy of specimens shows that the sample A contains no trace of corrosion (Figure 7A) unlike the specimen B (Figure 7B) where severe corrosion on the central reinforcement is observed. The upper bar is corroded along 20cm on its upper side and of 14.5cm on the lower side; the lower bar is corroded on its upper part on 19.5cm and 13.5cm on its lower part.

Figure 7: Pictures of sample A (diffusion/absorption) and B (migration/diffusion/absorption) extracted reinforcement.

The accelerated corrosion method is functional and provides significant results in a relatively short period of time (for this concretes formulation).
Structural essay

1. Preparation

Following the development of the accelerated corrosion method, large-scale testing was possible. A reinforced concrete slab of 3x3x0.15m was casted with a coating thickness of 2cm and a 10cm reinforcement horizontal spacing (Figure 8).

Ten months after casting, a first corrosion site was created; its size is about 10 cm lengths in the two directions. It is possible to carry out measurement with the two reference electrodes method without electrical connections with reinforcement.

2. Method

First of all, the step and the distance between electrodes were chosen equal to the size of the corroded zone: 10cm. In order to build a potential mapping with two reference electrodes, the first scan (Figure 9) requires that the electrodes are both in the measurement axis. Once the first measure is achieved, the device is moving in the same axis so, for the second measure, the first electrode is located in the past position of the second and so on. The second passage is performed in the same axis as the first, but the axis of the electrodes is perpendicular to the measures. Others are the same than the second passage but it is necessary to move the device of 10cm (the electrodes distance) in the axis of electrodes.

Figure 8: Picture about 3x3x0.15m reinforced concrete slab before casting

Figure 9: Schema of potential mapping method, using two reference electrodes
This method does not allow the building of a classical half-cell potential mapping reporting to SCE. Nevertheless it is possible to create an equivalent potential mapping where the reference is a point of measurement and its value is taken arbitrary as 0V in this study.

3. Results
The use of the device on the slab surface gives the following equivalent potential mapping (Figure 10). The potential at coordinates x=0, y=0 is arbitrarily chosen to 0V as previously mentioned. On this mapping we can see a first corroded area, numbered 1, where we used the accelerated corrosion method. The potential reaches \(-133V/E_{(0,0)}\) whereas distant from 30 cm the potential is about 90 to 140V higher. We can also detect a second corroded area with a potential reaching \(-148V/E_{(0,0)}\). This corrosion is not due to the accelerated method but to a rebar deformation. This deformation causes a local rise of rebar and therefore a very low coating thickness and a local carbonated corrosion.

\[\text{Figure 10 : Equivalent potential mapping using two reference electrodes with the detection of two corroded areas; } E_{(0,0)}=0V\]

4. Comparison
Figure 11 is a half-cell potential mapping carried out around the area 1 (Figure 10). This mapping is built using a saturated calomel electrode, to compare previous results with the ASTM C876-91 (Table 2) conclusions. The step measurement is about 1cm which is ten times finer than the previous system but in a smaller area (30x40cm).
According to ASTM C876-91, values comprised within the circle, are between -125 and -250 mV/SCE, their corrosion probability is about 50%. But given the potential gradients, we have the certainty that these bars are corroded in this area. Therefore, it is more interesting to look at the potential gradients rather than talking in terms of “absolute value” and corrosion risk.

**Table 2: ASTM C876-91 [7]**

<table>
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<tr>
<th>$E_{\text{corr}}$ (mV/SCE)</th>
<th>Corrosion risk</th>
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<tbody>
<tr>
<td>$E_{\text{corr}} &lt; -425$</td>
<td>Severe corrosion</td>
</tr>
<tr>
<td>$E_{\text{corr}} &lt; -275$</td>
<td>High (P &gt; 90%)</td>
</tr>
<tr>
<td>$-275 &lt; E_{\text{corr}} &lt; -125$</td>
<td>Intermediate (P = 50%)</td>
</tr>
<tr>
<td>$E_{\text{corr}} &gt; -125$</td>
<td>Low (P &lt; 10%)</td>
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</tbody>
</table>

The build of this equivalent potential mapping shows the feasibility of corrosion detection from the concrete surface without drilling and connecting the device to the rebar and therefore no requirement to check rebar continuity. These advantages reduce the number of manipulations which could make an easier work for automation measures.
**Conclusion**

To conclude, this article has helped to highlight, thanks to modeling, the influence of some parameters such as resistivity and the coating thickness for the half-cell potential measurements on reinforced concrete surfaces.

It has also been shown that it was possible to control the corrosion formation (size and location) with the introduction of a chloride migration process. This process has been used on a large slab, proving its correct operation in laboratory and large scale despite the significant reinforcement density. We could also see the feasibility of the two electrodes method through large scale testing.

We need to create other corroded areas of different sizes to compare modeling and experimental results. Moreover, the model input parameters (especially those involved in the equations of Butler-Volmer) will be determined to be representative to the concrete formulation, steel rebar and corrosion mechanism.

**References**


