Advanced numerical design for economical cathodic protection for concrete structures

R.B. Polder & W.H.A. Peelen
TNO Built Environment and Geosciences, Delft, The Netherlands

F. Lollini, E. Redaelli & L. Bertolini
PoliTecnico di Milano, Milano, Italy

ABSTRACT: Concrete structures under aggressive load may suffer chloride induced reinforcement corrosion, in particular with increasing age. Due to high monetary and societal cost (non-availability), replacement is often undesirable. Durable repair is necessary, e.g. by Cathodic Protection (CP). CP involves an electrical current through the concrete to the reinforcement from an external anode. The current causes steel polarisation, electrochemical reactions and ion transport. CP systems are designed from experience, which results in conservative designs and their performance is a matter of wait-and-see. Using numerical models for current and polarisation distribution, CP systems can be designed for critical aspects and made more economical. This paper presents principles and results of preliminary numerical calculations for design of CP systems, applied to protection of local damage in bridges (e.g. at leaking joints).

1 INTRODUCTION

Chloride induced reinforcement corrosion is the most important degradation mechanisms in concrete structures (Bertolini et al. 2004). Cathodic Protection (CP) is an effective and widely used method for reinstating corrosion protection (Pedeferri, 1996). CP involves an electrical current applied from an anode system through the concrete to the reinforcement. Current passage causes polarisation of the steel into the negative direction, electrochemical reactions at the electrodes and ion transport in the concrete pore solution. The polarisation resistance of the steel and the electrolytic resistance of the concrete govern the distribution of current and potential. With time the polarisation resistance will increase due to higher pH and lower chloride concentration near the steel and potential and current distributions will change. Presently, CP systems are designed without taking this into account, which results in conservative designs. With numerical models for current and polarisation distribution, CP systems can be designed for critical aspects and made more economical. Furthermore, the extent of protection outside the anode or deeper into the concrete (“throwing power”) can be predicted. This is illustrated by preliminary numerical analysis of a CP system applied to part of a bridge deck (Polder 1998).

2 MODELLING SETUP

2.1 Example structure

The structure for which the CP system was modelled consists of two parallel post-tensioned bridges over the river Dommel near ’s-Hertogenbosch, The Netherlands. Corrosion was due to de-icing salt leakage of the joints between the abutments and the deck, see Figure 1. Actual corrosion occurred of transverse bars within the first half meter from the joint edge. Deeper lying longitudinal bars and transverse bars further from the joint did not corrode. A CP conductive coating anode (AHEAD) was applied over one meter wide from the joint edge. Reference electrodes were placed near the reinforcing steel (for protection quality checking) and near the post-tensioning anchors (as a warning for reaching hydrogen evolution potentials) according to (EN 12696, 2000). Further details are given in (Polder 1998). Numerical simulations were made using the finite element package COMSOL Multiphysics. The objectives were to evaluate the distribution of polarisation and to assess the safety of the prestressing steel. Two humidity situations were simulated by varying concrete resistivity: one value for 80% relative air humidity (RH) and one for a RH higher than 90%, both at 10˚ C. The behavior of steel
2.2 Numerical model: geometry

The geometry of the real case is quite complex, so in order to reduce the computation time a 2D model of a part of the deck’s longitudinal cross section was set up. Numerical simulations carried out on two different lengths of the modelled part (3 and 5 m) showed that the length influenced the results, but the effect was significant only for the rebar farthest from the anode, whereas for active bars (under the anode) it was negligible. Therefore it was assumed that a cross section with a height of 0.8 m and 5 m long was representative of the relevant part of the bridge. The transverse bars have a concrete cover of 35 mm and are placed at 150 mm centre-to-centre distances, as shown in Figure 2. The three bars closest to the joint, which were actively corroding in the real case, have 32 mm diameter, the rest has 16 mm diameter. The longitudinal bars have a diameter of 16 mm and have 100 mm centre-to-centre distances.

In the 2D model, only transverse bars can be modelled in their real position; longitudinal rebars cannot be modelled as such. However, their presence cannot be neglected because such bars close to the anode do influence the current flow. Therefore the longitudinal bars were implemented as a second layer of transverse rebars close to the first layer. Each of these rebars was placed in between two (outer) transverse bars taking care to avoid overlapping with the transverse rebars. The real amount of steel was implemented, only the direction of these bars differs from reality. The diameter of these simulated bars was derived from the real steel surface area, about 0.5 m² of steel surface area per m² of concrete surface area. The longitudinal bars (simulated as transverse bars) had a concrete cover of 51 mm.

The bars in the upper side of the deck and the stirrups were modelled by mirroring the bars of the lower side. The presence of post-tensioning ducts and anchors, roughly in the middle of the deck thickness, was taken into account in the same way as the longitudinal bars. Taking into account ducts (or anchors) of 100 mm diameter placed at 1 m centre-to-centre distances, 5 bars per meter with a diameter of 20 mm were modelled. As in the real-life case, the anode had a width of one meter starting from the joint edge. The geometry of the model used is shown in Figure 2.

2.3 Numerical model: boundary condition

Due to the high electrical conductivity of metals compared to that of concrete, the rebars and the anode were assumed to be equipotential regions, and were not considered in the domain where Laplace’s equation was solved. The electrochemical behaviour of active and passive steel was described through polarisation curves that were used as boundary conditions in the model. These curves were expressed as Butler-Volmer type of relations between current density and potential for active steel:

\[
\begin{align*}
\dot{i}_a &= i_{corr,d} \cdot \left\{ \exp \left( \frac{2.303 \left( V - V_{corr,d} \right)}{b_{a,d}} \right) + \right. \\
&\left. - \exp \left( - \frac{2.303 \left( V - V_{corr,d} \right)}{b_{c,d}} \right) \right\} 
\end{align*}
\]

and for passive steel

\[
\begin{align*}
\dot{i}_p &= i_{corr,p} \cdot \left\{ \exp \left( \frac{2.303 \left( V - V_{corr,p} \right)}{b_{a,p}} \right) + \right. \\
&\left. - \exp \left( - \frac{2.303 \left( V - V_{corr,p} \right)}{b_{c,p}} \right) \right\} 
\end{align*}
\]

Here \( i \) is the normal component of the current density at the steel surface, \( i_{corr} \) is the corrosion current density, \( V \) is the potential at the concrete side of the interface, \( V_{corr} \) is the free corrosion potential, \( b_a \) and \( b_c \)
are the slopes of the anodic and cathodic polarisation curves. So, in order to describe thoroughly each polarisation curve, it is necessary to specify four parameters. In principle, each of these parameters may depend on environmental factors (wet, dry). The term $V - V_{\text{corr}}$, the polarisation from the corrosion potential due to current flow, is also termed overpotential.

Following previous work (Redaelli et al. 2006), for active bars it was assumed that the free corrosion potential was $-300$ mV/SCE in dry conditions and $-360$ mV/SCE in wet conditions and the corrosion current density in dry and wet conditions was 5 and 10 mA/m$^2$, respectively. The anodic and the cathodic slopes were taken equal to 75 mV/decade and to 200 mV/decade, respectively, identical for dry and wet conditions. For passive bars the parameters in expression (2) were considered independent of environmental factors. Free corrosion potential, corrosion current density, anodic and cathodic Tafel slopes were considered equal to $+100$ mV/SCE, 0.1 mA/m$^2$, 10000 mV/decade (i.e. virtually infinite) and 200 mV/decade, respectively.

The model also required specifying the properties of the material in terms of electrical conductivity. Since the electrical resistivity of the repair mortar used to repair corrosion damage spots had roughly the same value as the parent concrete (made with OPC/CEM I), it was assumed that conductivity was constant in space. A value for the electrical resistivity of 1000 $\Omega \cdot$ m was chosen for dry concrete and of 200 $\Omega \cdot$ m for wet concrete (Redaelli et al. 2006).

### 3 RESULTS

Different series of numerical experiments were carried out, varying the number of the modelled bars and the number of corroding rebars.

The first series of numerical experiments was carried out for a simplified geometry, with rebars in the lower part of the deck only and without post-tensioning steel. Models were solved with different values of anodic current densities, i.e. 10, 20, 25 and 35 mA/m$^2$. As shown in Figure 3, the lowest anodic current density that could polarize the three active rebars by at least 100 mV was found to be 35 mA/m$^2$. This value of anodic current density was used also for the rest of the calculations. The average values of the overpotential on the steel surface and the steel current densities are shown in Figures 4 and 5, respectively, both for dry and wet conditions. It should be noted that the anode is only present on one meter on the left side. In dry concrete the polarization of the three active rebars was about 160 mV. The rest of the rebars below the anode, which

---

**Table 1. Values of parameters used in equation (1) and (2) (Redaelli et al. 2006).**

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free corrosion potential of active</td>
<td>$V_{\text{corr,A}}$</td>
<td>Dry: $-0.30$  Wet: $-0.36$</td>
</tr>
<tr>
<td>steel</td>
<td>(V/SCE)</td>
<td></td>
</tr>
<tr>
<td>Corrosion current density of active</td>
<td>$i_{\text{corr,A}}$</td>
<td>5</td>
</tr>
<tr>
<td>steel</td>
<td>(mA/m$^2$)</td>
<td>10</td>
</tr>
<tr>
<td>Anodic Tafel slope of active steel</td>
<td>$b_{\text{a,A}}$</td>
<td>0.075</td>
</tr>
<tr>
<td>of active steel</td>
<td>(V/decade)</td>
<td>0.075</td>
</tr>
<tr>
<td>Cathodic Tafel slope of active steel</td>
<td>$b_{\text{c,A}}$</td>
<td>0.2</td>
</tr>
<tr>
<td>of active steel</td>
<td>(V/decade)</td>
<td>0.2</td>
</tr>
<tr>
<td>Free corrosion potential of passive</td>
<td>$V_{\text{corr,P}}$</td>
<td>Dry: $+0.1$  Wet: $+0.1$</td>
</tr>
<tr>
<td>steel</td>
<td>(V/SCE)</td>
<td></td>
</tr>
<tr>
<td>Corrosion current density of passive</td>
<td>$i_{\text{corr,P}}$</td>
<td>0.1</td>
</tr>
<tr>
<td>steel</td>
<td>(mA/m$^2$)</td>
<td>0.1</td>
</tr>
<tr>
<td>Anodic Tafel slope of passive steel</td>
<td>$b_{\text{a,P}}$</td>
<td>10</td>
</tr>
<tr>
<td>of passive steel</td>
<td>(V/decade)</td>
<td>10</td>
</tr>
<tr>
<td>Cathodic Tafel slope of passive steel</td>
<td>$b_{\text{c,P}}$</td>
<td>0.2</td>
</tr>
<tr>
<td>of passive steel</td>
<td>(V/decade)</td>
<td>0.2</td>
</tr>
</tbody>
</table>

![Image of Figure 3](image-url)
were passive, had a polarization of 500 mV. The polarization of passive rebars decreased with increasing distance from the anode: for instance in dry concrete the steel polarization is 40 mV at about 1.5 m from the anode and becomes 0 mV at 4 m, whilst in wet concrete the steel polarization is 110 mV at 1.5 m and 44 mV at 5 m from the anode.

The cathodic current density was 36–39 mA/m² (dry) and 33–36 mA/m² (wet) for the three active bars (see Figure 1) and 41 mA/m² (dry) and 36 mA/m² (wet) for passive steel bars under the anode.

The potential close to the anode obtained from the calculation was 0.9 V in wet concrete and 2.7 V in dry concrete; these values can be considered as an estimation of the feeding voltage of the CP system.

In the second series of simulations, bars were added in the upper part or in the middle of the deck (results not shown).

It was found that overpotentials and current densities decreased slightly for bars in the lower part of the deck. Placing steel inside the deck (where the post-tensioning is located) did not have a significant influence on potentials and current density of the lower steel.

Further simulations were carried out with a complete set of rebars in the lower and upper deck and post-tensioning in the middle, as shown in Figure 2.

For the third series of simulations the number of active transverse rebars was varied. From the joint edge step-wise 3, 5, 8 or 10 bars were assumed to be actively corroding. Bar #8 is located at a distance of 0.916 m from the joint and thus is the last bar directly under the anode; bar #10 is well outside the anode.

Figures 6 and 8 show the overpotential for active and passive steel for varying numbers of corroding bars in dry and wet concrete, respectively. Figures 7 and 9 illustrate the current densities on active and passive steel rebars for dry and wet conditions, respectively.

In general and in particular if high polarization is provided by a CP system, overprotection of the post-tensioning steel, ducts and anchors must be carefully regarded due to the possibility of hydrogen evolution (and subsequent embrittlement).

The absolute potentials of steel versus saturated calomel electrode at the position of the post-tensioning were calculated to check this possibility. The model was used to calculate the potentials of the post-tensioning steel for a varying number of active rebars for dry and wet concrete. The calculations showed that the most negative absolute potential reached was about $-150$ mV/SCE in dry conditions and $-220$ mV/SCE in wet conditions. They did not significantly depend
4 DISCUSSION

As mentioned above, the potential calculated through the numerical simulations allows calculating the overpotential which is the polarisation of the steel due to current flow. Assuming that this polarisation will relax to zero in the normal testing period of four to 24 hours after current switch-off, the “overpotential” could be interpreted as “depolarisation”. A value of 100 mV or more was taken as an indication of protection, in accordance to (EN 12696, 2000).

In the first (preliminary) set of numerical experiments, a cathodic polarisation of 100 mV for actively corroding bars in wet concrete was obtained with an anodic current density of 35 mA/m²; lower values of anodic current densities resulted in polarisation values lower than 100 mV, which was considered inadequate to protect active rebars. Much higher cathodic polarisation values were obtained on passive bars, about 500 mV for the rebars below the anode and 110 mV for rebars at 1.5 m from the anode. In dry concrete the steel polarization was about 160 mV for active rebars and 510 mV for passive rebars below the anode, and 40 mV at 1.5 m from the anode. The current density on the rebars (active and passive) below the anode was 37–40 mA/m². Compared to measurements in the field, these calculated current densities seem rather high.

The second set of simulations showed that adding steel inside the modelled cross section or on the opposite side of the deck from the anode, did not have a large influence on the current to the steel immediately below the anode. Overpotentials reached at steel inside the cross section (e.g. post-tensioning steel) were mildly negative.

In the third series, the number of corroding bars was varied in the lateral direction with respect to the fixed anode surface. Numerical simulations showed that actively corroding bars are protected as long as they are below the anode; active rebars outside the anode (even a few centimeters) received less current and were less polarised; the protection falls off strongly from the edge of the anode. Passive bars were well polarised, more or less independent of the number of corroding bars, also outside the anode (as with the first series), in particular in wet concrete.

In a general sense, it appears that current distribution in the concrete is under ohmic control.
The steel current densities obtained with the simulations are lower than would be normally expected in a CP system, typically 10 mA/m². This could be caused by several factors, such as assuming incorrect steel polarisation curves or boundary condition at the anode, incorrect values of concrete resistivities, making simplifications in the geometry or incomplete taking into account other effects.

Geometrical simplifications cannot be the main cause, as the real amount of steel and its approximate position were taken into account. Measurements on concrete resistivities in various climates suggest that more or less correct values were used. Other steel polarisation curves could be used, e.g. considering different values of corrosion potential and current density. However, it is hard to obtain polarisation curves from real cases and our estimate is the best guess we can make now. The most important factor that was not taken into account is the beneficial effect of the current itself: negative polarisation by CP is aimed at reinstating the passivation of the steel. Consequently, the polarisation curve of active steel should shift towards that of passive steel. Full treatment of this effect requires better insight into current- and time-dependent active/passive transitions of steel in concrete. It should be noted that for the high current density applied, passive steel showed polarisation values of about 500 mV. This suggests that a reduced corrosion rate due to current assisted passivating effects would sharply increase the polarisation. This would allow the current density to be reduced significantly. In practice, fixed voltage driven CP systems usually show a relatively high current density at start-up; then a strong reduction of the current in a matter of days to weeks. Further work is needed on this issue.

5 CONCLUSIONS

A finite element model was set up for cathodic protection of steel in concrete, taking into account the electrochemical properties of steel (active, passive) and concrete (dry, wet) as fixed values. The geometry of part of a bridge deck was simplified in 2 dimensions, including individual bars with realistic surface areas and positions; the anode covered only part of the underside of the simulated bridge deck, where some of the rebars were actively corroding. Local potentials and current densities were calculated using Butler-Volmer type steel polarisation behaviour. The amount of steel polarisation from the free corrosion potential (overpotential) is taken to represent the amount of depolarisation that is measured when the CP current is switched off, which is the usual way of checking the quality of protection.

Applying an anodic current density of 35 mA/m², 100 mV polarisation or more (indicating protection) was obtained for corroding bars under the anode in wet concrete; and for passive bars outside the immediate vicinity of the anode, both in lateral direction along the deck and deeper inside the cross section of the deck. Actively corroding bars would be protected only if they are under the anode. Steel inside the cross section would not reach very negative potentials that could allow hydrogen evolution (which should be avoided for prestressing steel).

Compared to practical CP systems after some time of operation, the current density seems quite high. A reasonable explanation is that the time-dependent beneficial effects of polarisation and current flow are neglected. Further work into modeling of passivating effects of CP with time is necessary. It is also foreseen that field data will be used to validate the model.

ACKNOWLEDGEMENTS

A short term scientific mission was carried out by Dr. Elena Redaelli in the framework of COST Action 534 “New materials and systems for prestressed concrete structures” (COST 534-1537) in June 2005 at TNO, which laid the foundation for this work.

The financial support of the Delft Cluster (Delft Cluster project CT02.30 “Smart Sustainable Management of Concrete Structures”) and TNO/TUDelft knowledge centre Durable Concrete Structures (DUCON) for Federica Lollini’s stage at TNO during 2007 is gratefully acknowledged.

REFERENCES