Abstract
The first known cathodic protections (CP) applied to reinforced concrete were installed more than 30 years ago. Unfortunately reliable data about those pioneer installations can hardly be found.

In our days the market of CP protection seems to be facing an illogical situation. On one hand the growing awareness by the professionals to efficiently master the development of corrosion has boosted the number of CP installations, while on the other side more and more cases of malfunctioning systems are to be known.

If CP as protection method is not questioned, most deficiencies of CP installations find their origin in:

- Inadequate preliminary diagnosis
- Inappropriate choice of protection system
- Insufficient and non customer tailored system design
- Underestimation of the difficulties to set up such a system
- Insufficient on site survey*
- Lack of quality control*
- Lack of training*
(*not discussed in this paper)

Keeping in mind as prime goal the durability of reinforced concrete (10, 20, 50 years) and considering the economic input at stake, any CP design must be considered as a risk management analysis.

Key words: Cathodic protection (CP) – corrosion - reinforced concrete - durability – drilled-in anodes – malfunctioning - risk management

The design of any CP system is primarily to be considered as a risk management analysis, of which above all the first step will be to know the object’s pathologies by an on-site diagnosis.
This point is being developed later on under chapter 1.

The conclusions of the diagnosis once established are discussed in order to integrate the customer’s specific needs into the CP installation design.
A quality control process such as ISO 9001 is an aid to better manage the entire process.

Supplementary considerations to any CP risk management analysis are shown by the 2 following field cases:

- CP of the piles and abutments of a highway bridge in Luxembourg
- An arch tunnel

It is not our intention to qualify any of the already existing systems but to converse about our experience in CP by drilled-in anodes.
1. Diagnosis

1.1 – A learning process

At first suspicion of hidden corrosion following process should automatically be started. The approach is often twofold:

- **PHASE 1**
  - Preliminary diagnosis
  - Reduced number of interventions
  - Reduced number of zones/defaults
  - First evaluation of the origin and quality of the pathologies
  - Determination if CP is relevant

- **PHASE 2**
  - Complementary, CP oriented, diagnosis is launched
  - General diagnosis conclusions
  - Discussions to integrate customer’s expectations? Durability of the object
  - Design and dimensioning of the customer tailored CP System
  - On site Pilot test of CP design (optional)
  - Issuing CP technical specifications

Process stops and/or other options are being taken into consideration.

Investigation measures shall be discussed chapter 1.2
The integration of diagnosis conclusions into a customer tailored CP design is shown while discussing the 2 field cases.
1.2 - Investigation methods

- At that level all information relative to the object’s history such as plans, previous diagnosis, survey reports are to be integrated.

- Visual inspection

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Cathodic Protection (CP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection of rust patches, eruptions</td>
<td>What is the importance of repair?</td>
</tr>
<tr>
<td>Detection of concrete spalling</td>
<td>What are the surfaces concerned?</td>
</tr>
<tr>
<td>Honeycombing, default of concrete density</td>
<td>What type of anode to choose?</td>
</tr>
<tr>
<td>Voids, Cracks</td>
<td></td>
</tr>
</tbody>
</table>

- Detection, localization and thickness of concrete overlay on rebars

  Reinforcement and rebar mapping by electromagnetic or radar survey

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Cathodic Protection (CP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rebar grid</td>
<td>What is the current density?</td>
</tr>
<tr>
<td>Local variations in rebar density</td>
<td>What type of anode to choose?</td>
</tr>
<tr>
<td>Average thickness of overlay, lack of cover layer</td>
<td>What kind of zoning to be set up?</td>
</tr>
</tbody>
</table>

- Electric continuity between rebars

  It is important to verify if the rebars are connected within and in between the tested areas before starting any corrosion measurement. These results shall be used as basis to the CP design.

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Cathodic Protection (CP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical continuity</td>
<td>What kind of zoning to be set up?</td>
</tr>
<tr>
<td>No electrical contact</td>
<td>What type of anode to choose?</td>
</tr>
<tr>
<td>Other metallic element</td>
<td>Re-installment of electrical contact</td>
</tr>
</tbody>
</table>

- Corrosion mapping

  The corrosion mapping will take in consideration following:

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Cathodic Protection (CP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical resistance*</td>
<td>What are the surfaces concerned?</td>
</tr>
<tr>
<td>Measurement of the natural electrochemical potential*</td>
<td>What type of anode to choose?</td>
</tr>
<tr>
<td>Corrosion rate measurement*</td>
<td>Re-installment of electrical contact</td>
</tr>
</tbody>
</table>

  The cross analysis of all these single measurements (*) as well as the mappings will allow following:
  - To avoid misjudgements
  - Directly appreciate on site the importance of the concerned volumes
  - It is mandatory that all these measurements are to be verified on site by break-ups

- Free and bound chloride profiles and carbonation

  It is important to operate a sufficient number of such tests. The resulting chloride profiles will allow to monitor the distribution in depth of Cl ions, their repetition will show their geographical distribution. The data are obtained by dissolving and potentiometric titration of the powders collected in various locations and depths of the object.
The carbonation depth is obtained on core samples and/or break-ups on site by single or multiple colour indicators. The so obtained mappings will allow to better focus onto the relevant testing areas and consequently be able to reduce the number of samplings. All these measurements must be operated on site and validated by laboratory.

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Cathodic Protection (CP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio Cl/OH</td>
<td>What is the density of the current?</td>
</tr>
<tr>
<td>Gradient Cl</td>
<td>What zoning / current distribution?</td>
</tr>
<tr>
<td></td>
<td>What type of anode to choose?</td>
</tr>
</tbody>
</table>

- **Break-ups**

During the diagnosis it is very important to anticipate the contractor’s future handling of his intervention and the difficulties he may face. Onsite break-ups help to a better understanding by:
  - Checking onsite the actual condition of the rebars
  - Validating, rejecting, optimizing the NDT testing

The break-ups should be operated in areas with no appearing defects as well as in suspect ones. Numbers and location will be defined through measurement and mapping evaluation.

**1.3 - Statistics and representativity**

Most of the investigations must be operated on site. The on site analysis of immediate results generates a learning process guiding the CP focused diagnosis and makes it evolve during the course of investigation process. This evolutionary approach produces better results from a statistical point of view as well as of the representativity of the data. This way to proceed can be described as “a controlled random investigation.”

**1.4 - From a “philosophical” point of view…**

It is clear that the above described approach which might at first look expensive only represents a fraction of the repair costs. Keeping in mind that modern intervention methods such as by roped party and/or mobile aerial work platform are quick, efficient and generate less and less hindrances. Trying to save money at that stage increases the risk in regards of execution price and the functionality in the design of the CP system.
2 Testing Case 1 - Highway Bridge OA 1028 - From diagnosis to CP design

2.1 - Some data
Location: Highway interchange Croix de Bettembourg (Luxembourg)

- Erection date: 1975
- Upper passage = 3 adjacent deckslabs
- Width of deckslabs: 42.50 m
- Length: 45.52 m
- Free height beneath deckslab: 4.35-6.00 m
- 14 piles: ± 474.00 m²
- 2 abutment walls: ± 500.00 m²

- Structure suffering from a lack of waterproofing: deckslab waterproofing – road joints – water pipes
- Piles show concrete spallings and have been experienced to contain high chloride levels
- The 2 abutments suffer from water penetration at the road joints and show concrete spallings
2.2 - CP design on piles

2.2.1 - Some results extracted from the diagnosis

---

**Fig 1**: Chloride profiles versus sampling depth
(Equipment: RCT from Germann Instruments A/S)

---

**Fig 2**: Percentage of chlorides/mass dry concrete relative to the height of piles
(Equipment: RCT from Germann Instruments A/S)
2.3 – Interpretation and conclusions

In regards of the diagnosis conclusions of which some of the elements are shown in figures 1, 2 and 3, a CP installation was the optimum solution.

a) Areas to protect
The cross analysis of the diagnosis data on figures 2&3 revealed that the CP could be limited to half the height of the piles.

b) Current density
Based upon the diagnosis data, the piles showed an average quality of concrete deeply polluted by the spreading of de-icing salt, with variable concrete cover layer, generally corroded with widespread pitting.

According to our experience and in relation to Paul Chess’s manual “Cathodic Protection of Steel in Concrete “, current density requirements for this type of steel condition is of 5-20 mA/m2 of steel.
c) Current distribution
Several factors were taken into consideration:
- Fig.2 - High gradient of chloride concentration from the bottom of the pile to the top
- Fig.1 - Highest chloride concentrations situate around or even behind the rebars
- Fig.3 - High gradient of corrosion activity from the bottom of the pile to the top
- Fig.3 - Ohmic resistances also show a high gradient with low to very low figures near the bottom (capillarity, % in chlorides)

The discussed facts imply an unequal distribution of protection currents with local changes of the ohmic resistances. Within the same zone currents must be as homogeneous as possible and current leakages towards the ground must be controlled.

d) What type of anode to choose
Two types were in question
- System of drilled-in anodes
- Surface anode of Ti-mesh embedded in a cover layer of shotcrete

Client’s requests
- 30 years of service life after repair
- The least possible disturbances in regards of the ongoing traffic
- Esthetic impact as neutral as possible

Within below chart we shall try to have an as balanced as possible evaluation by bouncing the pros and cons of the two types of anodes in regards of the risks and the imposed client’s requests.
<table>
<thead>
<tr>
<th>Network of drilled-in anodes</th>
<th>Ti-mesh</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 years of service life</td>
<td>+</td>
</tr>
<tr>
<td>Current density</td>
<td>+</td>
</tr>
<tr>
<td>+ installation of a grid of 40/40 cm</td>
<td>+</td>
</tr>
<tr>
<td>Currents distribution</td>
<td>+ possibilty to locally densify the anode implantation by increasing the number</td>
</tr>
<tr>
<td></td>
<td>+ en surface courante</td>
</tr>
<tr>
<td></td>
<td>- increase of zoning to meet the needs of an even current distribution. (resistance and corrosion activity variations)</td>
</tr>
<tr>
<td>Current leakages to the ground</td>
<td>+ by increasing the anode’s density</td>
</tr>
<tr>
<td>Handing</td>
<td>++ Intervention only on one side of the pile (1 drilling/cabling)</td>
</tr>
<tr>
<td></td>
<td>• Low surface treatment</td>
</tr>
<tr>
<td></td>
<td>• Common scaffolding</td>
</tr>
<tr>
<td></td>
<td>• Less dust</td>
</tr>
<tr>
<td></td>
<td>• Simple site implantation</td>
</tr>
<tr>
<td>Esthétics</td>
<td>+ nearly invisible</td>
</tr>
<tr>
<td></td>
<td>+ adding of 2-3 cm of concrete coverlayer</td>
</tr>
<tr>
<td>Intervention Time</td>
<td>+-</td>
</tr>
<tr>
<td>Major risks</td>
<td>- anode-cathode short circuiting: can be reduce by monitoring the rebar spacing and checking the drilling holes with a specialized device</td>
</tr>
<tr>
<td></td>
<td>- short circuiting</td>
</tr>
<tr>
<td></td>
<td>• Alien metallic items</td>
</tr>
<tr>
<td></td>
<td>• Uneven/lack of coverlayer</td>
</tr>
<tr>
<td></td>
<td>• High risk of debonding</td>
</tr>
<tr>
<td></td>
<td>• Risk of acidification</td>
</tr>
<tr>
<td>Work difficulties</td>
<td>- Drillings</td>
</tr>
<tr>
<td>Costs</td>
<td>10 to 20 % more</td>
</tr>
<tr>
<td>Easy to enlarge</td>
<td>++</td>
</tr>
<tr>
<td>Maintenance</td>
<td>+</td>
</tr>
<tr>
<td>Easy to repair</td>
<td>+</td>
</tr>
</tbody>
</table>
Some comments about the shotcrete adherence

The adherence of the shotcrete cover layer is of prime importance for a proper functioning of a Ti mesh-CP system and any loss in adherence is resulting in a local malfunctioning of the system:

- The preparing of the support is very cumbersome as the end result must guarantee a minimum adherence of 1.5MPa.
- The outcome is very much depending on the skill of the applying technician
- In order to avoid voids, segregations or detachments from the support a special attention must be drawn to elements such as corners and angles.
- It is sometimes impossible to properly cure the fresh concrete
- It is of prime importance to guarantee a homogeneous concrete mixture
- The technique is difficult to set up in confined spaces
- The technique is difficult to set up on surfaces with a complicated geometry.
- Return of experience

Some returns of experience

a) Debonding
   In some cases it appears that well prepared surfaces generate a debonding of the cover layer. This phenomenon takes place during the cold seasons. It seems that high stresses might occur between the chloride polluted substrate and the chloride free shotcrete and develop debonding.

b) Shotcrete resistivity
   The even distribution of CP current is function of mortar resistivity which depends on:
   - Type of mortar
   - Means of projection dry/wet
   - Mixing time
   - Handling of mortar (skills)

   One seldom finds shotcrete specifically formulated for CP:
   - known and documented resistivity
   - resistant to the acid production as a result of CP chemical reaction

2.2 CP on abutments

The abutments of the bridge were treated with a Ti mesh embedded in a cover layer of shotcrete. The choice to apply that specific system was the customer’s.
The application technique was on wet bases
The mortar was delivered on site in ready mixed bags.
The mortar’s electrical resistivity was certified and documented upon lab tests by the producer.
An object tailored application procedure and quality control were set up.

2.3 Conclusions 8 years after being set up

After being up and running for eight years, both systems do meet the EN 12696 standards, the polarization/depolarization values give satisfactory results. Nevertheless a recent site survey showed that out of a total of 450m² of applied shotcrete an area of approx. 3m² was debonding from its support. This area had not been identified during the quality control.
3 Development of drilled-in anodes

3.1 - History

Drilled-in anodes were first used in Denmark in 1986 and are still working successfully on a bridge from 1987 onwards. From that time to the present days their gradual evolution has made this type of anode more durable and simpler to install. Some of the developments are listed hereafter.

- Changing the coating on the titanium from platinum to MMO (mixed metal oxide) which is a ruthenium oxide and tantalum oxide mix. This gave an increase in the design life of the anode
- Changing the resistor location from the end of the cable feeder into the body of the anode. This made the wiring simpler and much easier to conceal, allowing its use on historic facades.
- The insulated cable feeder allowed the use of the anode in congested steel areas where electrical short circuits are most likely to happen.
- Replacing the anode rod by a perforated tube allows its homogeneous drowning into the sealing mortar. This enhances the current distribution allowing reducing the current density with the direct consequence of the improvement of the anode’s service life.
- Using sealing mortar instead of carbon based water soluble backfill makes the use of anodes possible in places where water leakages might occur.
- The improvements in the anode connection make the PC network-implementation faster and safer.
- A new specific design for soffit installations makes overhead installation faster and safer.

3.2 - Testing case 2 - CP Protection along transversal cracks in a tunnel

This tunnel is suffering from chloride-induced corrosion along transversal cracks. These cracks appear systematically at each 1.5m.

The CP purpose is to protect:
- As an active measure the cracked areas
- As an active measure the footage of the arch
- As a preventive measure the area between the two cracks

To evaluate the performance of drilled in anodes a pilot installation was set up along two neighboring cracks.

Figure 4 describes this trial.
Fig 4: CP design along 2 cracks

<table>
<thead>
<tr>
<th>Date</th>
<th>Comment</th>
<th>Ref. 1 (mv)</th>
<th>Ref. 2 (mv)</th>
<th>Ref. 3 (mv)</th>
<th>Ref. 4 (mv)</th>
<th>Ref. 5 (mv)</th>
<th>Ref. 6 (mv)</th>
<th>Ref. 7 (mv)</th>
<th>Ref. 8 (mv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/06</td>
<td>Natural potentials</td>
<td>-329</td>
<td>-100</td>
<td>-97</td>
<td>-84</td>
<td>-100</td>
<td>-94</td>
<td>-307</td>
<td>-339</td>
</tr>
<tr>
<td>06/06 23h20</td>
<td></td>
<td>-530</td>
<td>-239</td>
<td>-324</td>
<td>-237</td>
<td>-210</td>
<td>-421</td>
<td>-668</td>
<td>-458</td>
</tr>
<tr>
<td>11/06</td>
<td>Implementation</td>
<td>4.40</td>
<td>0.091</td>
<td>-574</td>
<td>-375</td>
<td>-275</td>
<td>-254</td>
<td>-315</td>
<td>-457</td>
</tr>
<tr>
<td>11/06</td>
<td>In operation</td>
<td>4.40</td>
<td>0.091</td>
<td>-574</td>
<td>-375</td>
<td>-275</td>
<td>-254</td>
<td>-315</td>
<td>-457</td>
</tr>
<tr>
<td>12/06</td>
<td>Delta polarization</td>
<td>-331</td>
<td>-126</td>
<td>-123</td>
<td>-117</td>
<td>-134</td>
<td>-132</td>
<td>-317</td>
<td>-345</td>
</tr>
<tr>
<td>12/06 Après 17h00</td>
<td>4.34</td>
<td>0.084</td>
<td>-573</td>
<td>-392</td>
<td>-290</td>
<td>-275</td>
<td>-330</td>
<td>-483</td>
<td>-679</td>
</tr>
<tr>
<td>21/06</td>
<td>Delta polarization</td>
<td>4.34</td>
<td>0.084</td>
<td>-573</td>
<td>-392</td>
<td>-290</td>
<td>-275</td>
<td>-330</td>
<td>-483</td>
</tr>
</tbody>
</table>

Fig 5: Polarization/depolarization values

The analysis of above data shows that it is possible to ensure the protection of the two cracks described in fig.4 with a current density adjusted to 3 m A/anode. The above described CP design enables protection:

- Along the cracks
- At the footage of the arch
- Within the area between the two cracks; the polarisation radius per anode is surprisingly effective
4. Conclusion

Cathodic Protection is definitely a technique able to solve number of corrosion problems. It is also a technique where risks of malfunctioning are real and can often lead to dramatic situations.

The risk is manageable under the condition we take past experiences into account and integrate the lessons into future CP design.

Even if Ti mesh is considered as the reference installation for large surfaces, drilled in anodes, until recently only used for small areas, may become an alternative for following reasons:

- The progress made in the development of drilled-in anodes is encouraging, and their set up should be less risky.
- May be new developments and new specific procedures will help to master the adherence problems met in Ti mesh systems.
- Master the encapsulation of Ti mesh.
- Master the quality assurance of the shotcrete’s resistivity.
- For structural reasons quite some objects do not allow an overlay of mortar.

Up until now the best solution remains to combine the advantages of different techniques available on the market into a customer tailored CP system specific to each object.

For example in the case of the OA 1028 the current leakages to the ground at the bottom of the piles are compensated by the addition of ground anodes. This solution has enabled a gain of polarization of 20 to 40 mV per pile at ground level.