Cathodic Protection of Reinforced Concrete Structures in The Netherlands – experience and developments

Cathodic protection of concrete – 10 years experience

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Cathodic protection (CP) of reinforcing steel in concrete structures has been used successfully for over 20 years. CP is able to stop corrosion in a reliable and economical way where chloride contamination has caused reinforcement corrosion and subsequent concrete damage. To new structures where corrosion is anticipated, cathodic prevention can be applied. Recently the state-of-the-art was described and a draft European standard has been published. In The Netherlands, CP was introduced in 1987 and since then 20 full scale projects were executed. In all cases, alternatives such as replacement of the elements or conventional repair were considered, but CP was preferred for reasons of practicability, safety and durability. Most structures with CP in The Netherlands concern mixed in chloride and relatively small precast concrete elements. In 1996, CP was applied to parts of a post-tensioned bridge. Based on practical experience, a National Technical Recommendation was published. This paper describes the history, the principles and three examples.

Key words: **concrete, corrosion, cathodic protection.**

1 Introduction

Cathodic protection (CP) of reinforcing steel has been applied to concrete structures with corrosion damage for over 20 years. World wide experience shows that CP prevents further damage in a reliable and economical way for a long time. CP is particularly suited in cases where chloride contamination has caused reinforcement corrosion. Application started in the USA in the 1970's on bridge decks suffering from corrosion due to de-icing salt penetration resulting in severe damage to the concrete. In the 1980's new anode materials became available. Subsequently, CP was applied to buildings, marine structures, tunnels and bridge substructures. A further development is application of CP to new structures where corrosion is anticipated within the service life, which is termed cathodic prevention (Bertolini et al. 1996, Pedeferri 1997). Recently the state-of-the-art was described (COST 1997) and a draft European standard has been published (CEN 1996).

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In The Netherlands, CP was introduced in 1987 and since then, one or two full scale projects were made every year until 1993. In all cases, alternative options such as replacement of damaged elements or conventional repair were considered, but CP was preferred for reasons of practicability, safety and durability. In 1994 three, in 1995 six and in 1996 five installations were completed and energised. This growth was due to more economical anode materials (such as conductive coatings) and increased awareness of the advantages of CP. Based on experience in the field, a Technical Recommendation was published (CUR 1996). In 1996, the Ministry of Transport (Rijkswaterstaat) has commissioned their first project by applying CP to parts of a post-tensioned bridge. After shortly explaining the principles of CP, this paper describes three examples.

2 Principles of cathodic protection of steel reinforcement in concrete

The normal situation of steel reinforcement in concrete is passivity. This is a state of almost negligible corrosion rate, caused by an atomically thin oxide film on the steel surface, which is stabilised by the high pH in concrete (about 13). This passivation may be lost by two mechanisms: either carbon dioxide ingress, which reduces the pH to values about 9 (carbonation), causing a more or less uniform loss of passivation, or the presence of chloride ions, which locally break down the passive film starting pitting corrosion. Chloride may be either cast in as a set accelerator or penetrate from de-icing salts or sea water. Corrosion is an electrochemical phenomenon, in which the potential of the steel and the exchange of electrical current between steel and concrete pore solution play important roles (Schiessl 1988, Broomfield 1997). In the passive state, the potential of the steel is relatively positive, due to a reaction of oxygen at the steel surface, consuming electrons (termed the cathodic reaction). When passivation is lost, iron passes into solution as ferrous ions (Fe^{2+}), leaving excess electrons in the steel, which make the potential more negative; this reaction is termed anodic. Potential differences between cathodic and anodic sites cause currents to flow in the concrete pore liquid, accelerating the steel dissolution reaction. The overall reaction rate (in atmospheric concrete structures) is thought to be limited by the electrolytic resistance of the concrete. The ferrous ions react with hydroxide ions formed at the cathodes and with more oxygen to form various solid hydrated ferric oxides, commonly called "rust". These corrosion products are more voluminous than the original steel. The net effect is expansion, causing tensile stresses in the surrounding concrete cover. After relatively small amounts of steel have been transformed into corrosion products, concrete cracks and spalling or delamination occurs. Cracking and spalling have to be taken as a warning of further decay: when left to corrode, the steel bar diameter may decrease below structurally acceptable values. Normally, spalled concrete is repaired using new, alkaline and chloride-free concrete (Schiessl 1992, Bijen 1989). However, if chloride ions remain, corrosion can start again, which may relatively soon cause new damage to the concrete.

Cathodic protection is based on changing the potential of the steel to more negative values, reducing potential differences between anodic and cathodic sites and so reducing the corrosion current to negligible values. The reduction of potential is called polarisation. In practice, this is realised by mounting an external electrode, the anode, on the concrete surface, connecting it with the positive terminal of a low voltage direct current source, while connecting the negative terminal to the reinforcement cage, as illustrated in Figure 1. Through the reinforcement cage, electrons flow to the steel/concrete interface, increasing the cathodic reaction, which produces hydroxide ions from oxygen and water. The hydroxide ions migrate through the concrete cover to the anode where they are oxidised to oxygen and electrons. The electrons flow to the current source, which closes the electrical circuit. As a result of this current circulation, cathodic reactions at the steel are favoured and anodic reactions are suppressed. Relatively moderate current densities are able to restore passivation and have various beneficial chemical effects (Pedeferri 1997, COST 1997): hydroxide ion production at the steel increases the pH; migration of chloride ions to the anode, away from the negatively charged steel. The required polarisation makes CP a permanent method: the current must flow during the remaining service life of the structure. Due to the chemical changes (increase of hydroxide and reduction of chloride at the steel), the protection improves in the course of time and theoretically the current may be reduced. If the current is interrupted, the protection will remain intact for some time. For a uniform distribution of the protection current, the steel must be electrically continuous and the concrete must have a reasonably homogeneous conduction. At any time and place, short circuits between the anode and the steel must be avoided. Possible negative effects of CP are: degradation of concrete around the anode, which is only significant at high current densities; and too strong negative polarisation of stressed high strength steel (evolution of hydrogen may cause embrittlement of high strength steel). When overprotection is avoided, these negative effects are negligible.

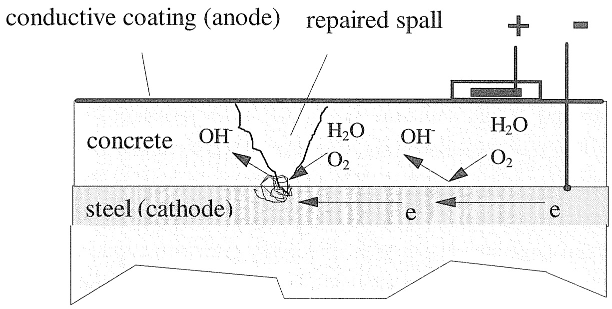

Fig. 1. Principle of cathodic protection of steel in concrete (with conductive coating anode).

The quality of protection offered by a CP system is tested regularly (normally a few times per year). Because of the complexity of the causes of corrosion (chloride, pH, moisture) it is not possible to predict a fixed value for the potential or the current. As mentioned before, overprotection should be avoided. As a general measure of the quality of cathodic protection, the amount of polarisation that actually takes place in the structure is measured: as long as CP causes a certain minimum amount of polarisation, it may be assumed that the polarisation is strong enough to suppress corrosion to an insignificant level. This is tested for by interrupting the protection current and monitoring the subsequent change of the steel potential over periods up to 24 hours at several representative points in the concrete structure using embedded sensors (called reference electrodes). With the current switched off, the steel potential relaxes from polarised to non (or less) polarised; this test is called depolarisation. Empirically, a minimum depolarisation of 100 mV is considered indicative of sufficient protection for atmospheric concrete structures. For submerged or buried structures other criteria are applied (Linder 1994, CEN 1996, Page 1997, Chaudhary & Chadwick 1997)

One of the main advantages of CP is that only spalls and detached parts need to be repaired. Structurally sound but chloride contaminated concrete can remain in place, because CP takes over the protection. Compared to conventional repair, the cost of repair may be reduced considerably. The added cost of the CP system is justified because of the increased reliability of the protection to the steel.

3 Practical application of cathodic protection

Design of practical systems for cathodic protection must be carried out on a structure-to-structure basis. Concrete structures differ widely by properties such as concrete composition, cover depth and steel layout, chloride content and exposure to moisture. Each CP system must be designed individually, based on a proper survey of specific details of the structure. First a basic design is made, specifying the type and geometry of the anode, the electrical set-up, the reference electrodes and the monitoring procedures. The most widely used anode types are conductive surface coatings, activated titanium mesh embedded in cementitious overlays or titanium strips inside the concrete. Electrically, a CP system may be divided in separate zones, each with their own current source (transformer/rectifier), if the resistivity of the concrete differs significantly over the structure due to differences in concrete composition (Polder 1996) or exposure to moisture and chloride. Particular anode layouts and division in zones may be necessary to obtain a sufficiently uniform current distribution. Reference electrodes are placed in typical locations. Monitoring procedures include the frequency of measurements and additional tests such as current distribution measurements.

In the execution stage, the results of the preliminary investigation are verified. Spalls are made good by applying conventional mortar repairs. The concrete surface is prepared to provide durable bond to coatings or overlays. The anode (and overlay) is applied and electrical connections, wires, reference electrodes and transformer/rectifiers are installed. If short circuits occur, they should be corrected. After sufficient curing of mortars and coatings, the current is switched on. A period of several months is taken to adjust the current to values which provide protection, as observed from frequent depolarisation measurements. If these are satisfactory, the normal maintenance scheme begins. Usually, this involves two to four sets of depolarisation measurements per year. In an increasing number of systems, remote control is installed, providing dataloggers and modem access from the office of the contractor or the consultant. However, every system should be visually inspected once a year to check the integrity of electrical parts and to make sure that corrosion damage to the concrete is absent. A report is made to prove the client that his investment in a CP system keeps the structure in good condition.

4 Experience with CP

World wide, many hundreds of concrete structures have received CP. Apart from trivial failures, they all operate satisfactorily and corrosion damage appears to be virtually absent. Recently, several case studies and papers describing many years of experience have been published (Schreyer & Haldemann 1997, Chaudhary & Chadwick 1997, Tettamanti et al. 1997, Gedge & Sheehan 1996). Over 20 CP systems operate in The Netherlands today. The author has been involved in engineering the majority of these cases. On a more or less regular basis, data are still being reported on their operation. Three widely varying cases are described below, which are interesting for their details. Also, some of the design considerations are given and lessons learnt are reported.

4.1 *Cantilever beams in two apartment blocks, Tilburg*

4.1.1 History

This case concerns 2448 precast concrete cantilever beams supporting balcony slabs in two housing blocks of 17 floors at Tilburg, The Netherlands, built in 1972. Many beams had suffered from severe corrosion damage due to calcium chloride added to the fresh concrete as a set accelerator. Cracking of concrete occurred after less than 10 years of service. A polyurethane coating was applied, but in a few years damage reappeared. In 1990, it was realised that a more durable solution was needed. Replacement of the elements would cause too much inconvenience to the inhabitants, so it was decided to apply cathodic protection.

4.1.2 Design and execution

The anode layout was unconventional, with a strip of activated titanium in a hole drilled along the main axis of the beams and filled with cementitious grout, as shown in Figure 2. In laboratory tests of current distribution to individual rebars in similar beams, the optimal anode layout was found (Polder & Nuiten 1991, Polder & Nuiten 1994). The rebar continuity within each of the elements was good and the cover to the steel showed little variation. Continuity between the elements was not always present, so a reinforcement connection was necessary in each beam. The system would operate under constant current control. To control the current accurately and due to the limited capacity of the available rectifiers, zones of 18 beams were made, separated for orientation North and South. A hollow coring drill of ∅ 35 mm was used for making the boreholes. The absence of short circuits was tested using a DC resistance device. Short time polarisation was applied to each beam and the subsequent change of the steel potential with respect to a reference electrode on various positions on the concrete surface was measured. The shift values were similar on all locations on the surface, showing that the current distribution within the beams was quite uniform. If connections between rebars and negative wiring was inadequate, this was easily detected by this test. The AC-resistance of all beams (anode to cathode) was tested before energising. The variation was between $\frac{1}{2}$ and 2 times the mean value. After commissioning, a few short-circuits could be detected as they decreased the driving voltage of the particular zone (at the preset current level) significantly. Several repair mortars were checked for sufficient current conduction. One mortar had a very high resistance and was rejected; the others were accepted. After slight modification (see below), the testing procedure was used in later projects and laid down in (CUR 1996).

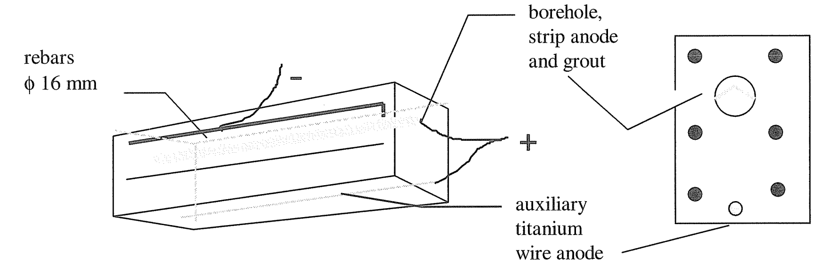

Fig. 2. Cantilever beam with strip anode in cement-filled borehole, Tilburg.

4.1.3 Performance during six years

Depolarisation readings with respect to manganese dioxide reference electrodes (RE) have been taken at least twice a year since energising at the end of 1990. Figure 3 shows average data of 34 zones of one installation. In a few zones minor adjustments to the current levels were made to reduce too high depolarisation values or to increase relatively low depolarisation. The average current density is about 8 mA per m^2 steel surface, corresponding to 35 mA/m^2 anode surface, which is well below the maximum anode current density level allowed (108 mA/m^2). The driving voltages show some variation with the season, from 1.3 V in summer to 2.5 V in winter. Lower temperatures increase the resistivity of the concrete (Bürchler 1996, Bertolini & Polder 1997). For one building, the average depolarisation values were between 110 and 150 mV (after 4 hours) and between 180 and 250 mV (after 24 hours); they show a slow increase over the years. Twice, depolarisation measurements were carried on for about 9 days. These "long term" depolarisation values were substantially (15 to 25%) higher than those after 24 hours. This shows, that evaluating

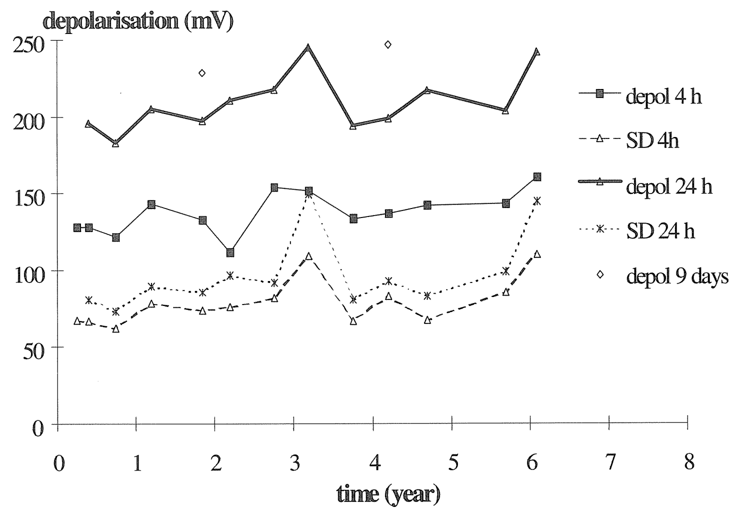

Fig. 3. Average (solid lines) and standard deviation (hatched lines) of depolarisation of 34 zones, Tilburg.

the depolarisation of the steel over a 24 hour period is on the safe side. Within each set of depolarisation data of 34 zones at one point in time, considerable variation was present. Typical standard deviations were 80 mV for an average of 140 mV. Probably this is due to local differences in wetting (exposure, some leakage of drains). All winter datasets have higher standard deviations than the preceding or following summer datasets. This is also found in the other building, so the cause is an external effect, probably connected with the weather. The results show that CP in both buildings has performed satisfactorily. The high stability of the electrical results in the course of time may be caused by the relative absence of environmental influences. The anode is embedded deeply inside the concrete and the elements are sheltered from most of the rainfall by the slabs on top. The temperature is probably the only varying factor. In another CP project, with the anodes in an overlay on the upper side of balconies exposed to rain, much stronger variations with season were observed (Nuiten 1990).

4.2 *Gallery slabs and frames, Groningen*

4.2.1 History and Preliminary Investigation

This apartment flat was built in 1957. It consists of gallery slabs and supporting frames, which were precast on site. The concrete had been coated since the 1960's. In the early 1980's, cracking due to corrosion occurred, which was repaired with polymer mortar. Cracking and spalling reappeared in about 5 years. Cover depths were 20 to 30 mm and carbonation was 0 to 20 mm. The total chloride content was between 0.3 and 0.8% (average 0.6%) by mass of cement, apparently added to the concrete mix. The cement was ordinary Portland cement. Steel continuity was poor, probably due to corrosion of binding wires. Corrosion was still active and the damage was expected to increase in the course of time. Both conventional repair and replacement of the elements were very costly and would strongly disturb the inhabitants. CP was chosen as the most favourable option.

4.2.2 Design and Execution

Because the exposure to rain of all elements is similar, one electrical zone of 600 m^2 concrete surface was made. As drawings were absent, the steel surface area was unknown. It was considerably less than 1 m^2 of steel surface per m^2 of concrete surface. Spalls were repaired using a trowelling mortar or a flowing mortar (both cementitious with polymer modification). Steel continuity was installed by welding steel wires to all bars. A conductive primer with a semi-conductive polymer and a low graphite content together with twisted silver wire ribbon as a primary anode made up the anode system. A cosmetic top coat was applied. The layout is given in Figure 4. To the top surface of the slabs a normal polymer floor coating was applied. Fourteen graphite RE's were evenly distributed over the slabs and the frames. The system operates under constant voltage control, with a maximum of 2.0 V. Potentials were monitored by datalogger with remote control and data acquisition by telephone.

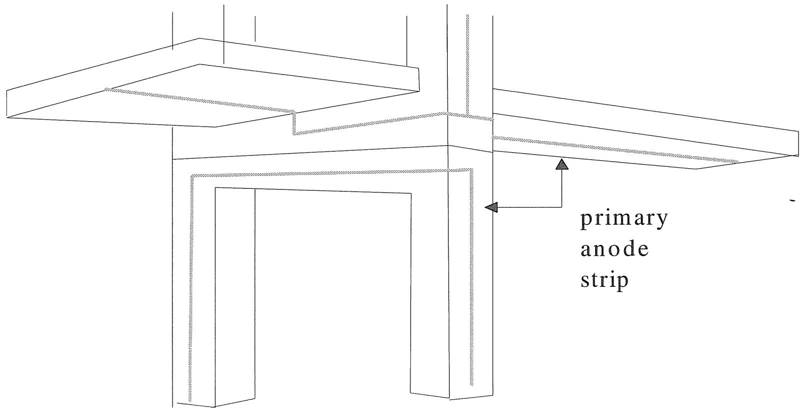

Fig. 4. Layout of slabs and frames with conductive coating on all faces except top face of slabs, Groningen.

4.2.3 Repair mortar compatibility

For electrical compatibility testing, 100 × 100 × 50 mm^3 prisms with two embedded brass bars were cast. For each of the two proposed mortars, four specimens were exposed in a fog room (20°C and >95% relative humidity (RH)) and four in a climate room with 20°C and 80% RH. The (mortar) resistance between the brass bars was measured with 108 Hz AC for eight weeks. Readings were converted to mortar resistivity using cell constants obtained with solutions of known conductivity. The exposure climates represent two extreme situations: very wet concrete in an exposed structure (fog room) and a sheltered structure in equilibrium with the annual-average RH in Western Europe (20°C 80% RH). In general, a repair mortar is considered suitable if its resistivity is no more than twice and no less than half the resistivity of the concrete. This procedure has been adopted in the Dutch Technical Recommendation (CUR 1996), including reference values for concrete resistivity as a function of exposure and cement type, based on previous research (Polder 1996, Polder & Ketelaars 1991). For comparison, two cores were taken from the structure and the resistance was measured between steel plates pressed to the two faces via soap impregnated cloth, after exposure first in 80% RH and then in the fog room.

The resistivity was calculated by simple geometric conversion. The cores had a resistivity of 600 to 1200 Ωm in 80% RH and about 250 Ωm in the fog room. Both dry and wet values are relatively high for Portland cement concrete (COST 1997), which is probably due to partial carbonation. For judging the resistivity of the repair mortars, the value in 80% RH was considered most important because of the sheltered exposure of the structure. In 80% RH, the resistivity of the flowing mortar was about 650 Ωm and that of the trowelling mortar about 1200 Ωm. Both mortars were judged to be electrically compatible.

4.2.4 Performance

The electrical operation of the system was evaluated during four months after commissioning in September 1994. The average depolarisation in 24 hours was 150 mV, which is satisfactory with respect to the criterion (>100 mV). The standard deviation (n = 14) was 72 mV. The current density is relatively low: 600 mA flows through 600 m^2 concrete surface (containing possibly 300 m^2 steel surface). Regarding the presence of the coating system and the moderate rain exposure, this was considered reasonable. It was concluded that the system operates satisfactory. Later measurements (3 to 4 per year) until two years after commissioning have confirmed this. From 1993 to 1996, CP has been applied to four buildings of this type with similar results.

4.3 *Abutments of a post-tensioned bridge, river Dommel*

4.3.1 History

In 1996, the Dutch Ministry of Transport (Rijkswaterstaat) has applied CP to their first project. It concerns two parallel post-tensioned bridges of 14 m wide, locally suffering from corrosion due to de-icing salt leakage in the abutment joints. Chloride had penetrated deeply into the underside of the bridge deck over about half a meter from the joint. Conventional repair by cutting out spalls and contaminated concrete and replacing with new concrete was technically possible. However, the working space was limited to less than half a meter height, so shotcrete could probably not be applied with the required attention. Consequently, the new concrete had to be cast from the top of the deck. This would disturb the traffic to an unacceptable extent. Considering all possibilities, CP was preferred as the least disruptive method with good expectation of durability.

4.3.2 Design and execution

The structure was made using OPC. The surface area of the reinforcement in the abutments was equal to the concrete surface. Cover depth was about 30 mm and carbonation depth was practically zero. In the abutments, the post-tensioning steel was lying at a depth from the underside of at least 250 mm. A conductive coating anode was applied to a zone of one meter wide from the joint and a silver wire ribbon primary anode was installed parallel to the joint, as illustrated in Figure 5.

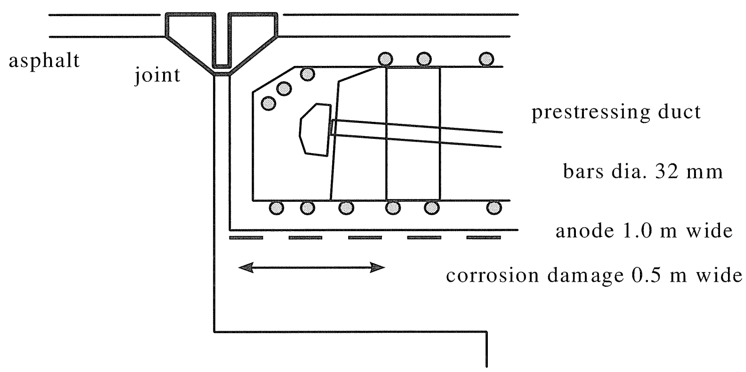

Fig. 5. Cross section bridge abutment, river Dommel.

The total protected area comprised four separate parts of 1 m wide by 14 m long (2 North, 2 South). As the exposure was expected to be quite homogeneous, the four parts were put together in one electrical zone. The presence of prestressing steel was taken into account during the design of the system. Sixteen RE's for monitoring the polarisation of the post-tensioning steel were installed at the depth of the ducts. For expected optimal long term performance and stability, manganese dioxide RE's were chosen. Close to the mild steel reinforcement, sixteen graphite RE's were placed for normal protection monitoring. The monitoring frequency is four times per year. The criteria were as follows:

- protection of reinforcing steel: (average) depolarisation in 24 h > 100 mV
- safety of prestressing steel with regard to hydrogen embrittlement potentials: (all individual) polarised potentials more positive than –850 mV vs Ag/AgCl; considering the scatter in the base potentials of the RE's, it was decided to set the safety limit 50 mV more positive than is necessary according to (CEN 1996).

4.3.3 Performance

The system was energised in October 1996. The performance during five months is summarised as follows. The average depolarisation over 24 h has been > 100 mV since about 3 months from the start, at relatively mild driving voltages, despite low temperatures (about 0°C). In March 1997 (+8°C) the average depolarisation was 120 mV; the standard deviation was 37 mV (n = 16).
The depolarisation over 4 h is less in all cases (80 mV in March 1997). Apparently this system needs more than a few hours to depolarise; judging depolarisation for short periods like 4 hours is not a good criterion here and will lead to overprotection. The polarisation of the prestressing ducts is very mild; typical values are about –200 mV vs Ag/AgCl. The current distribution was relatively stable over time. One field draws significantly more current than the other three .

In June 1997, the 24 hour depolarisation of the reinforcing steel was below 100 mV (average about 90 mV). In order to improve the level of depolarisation, the driving voltage was deliberately increased to 2.5 and for a short time to 3.0 V. The depolarisation improved. However, in August 1997, during a long hot and dry period with temperatures near 30°C, the current density was very low (less than 1 mA m^{-2}), clearly due to increased concrete resistivity; the average depolarisation was well below 50 mV. In October the average depolarisation was again over 100 mV (at 2.5 V with a current density about 3 mA m^{-2}). In all cases, significant scatter was present within the measurements. After one year of operation, despite short term deviations from the pre-set criterion (100 mV depolarisation), the system was judged to operate satisfactorily. It is expected that over the years the depolarisation will improve systematically.

5 Concluding remarks

In The Netherlands cathodic protection was applied successfully to about 20 structures during the past ten years. CP was shown to stop corrosion of reinforcement effectively, including cases where previous conventional repairs had not stopped further development of corrosion induced damage. In the medium to long term, CP may save a considerable amount of money compared to (repeated) conventional repairs. The design and execution require specific expertise and attention. Repair materials must have similar electrical resistivity to the concrete of the structure. Test methods and reference data are available. Various anode types are available and different layouts have been developed to suit the particular requirements of many structures and their owners, showing that CP is a flexible method. Over the last ten years, the design of installations could be simplified because of better understanding and increased confidence in the technique. The number of zones could be reduced due to improved insight in the role of the electrical resistivity of concrete. It appears to be safe to evaluate depolarisation over 24 hours instead of 4 hours. It is recognised that considerable variation may be present in depolarisation datasets and statistical treatment is necessary. The experience was laid down in a national Technical Recommendation, giving guidelines for many practical issues. In a recent case it was found that the presence of prestressing steel in ducts does not have to preclude the use of CP. The polarisation of the prestressing ducts was shown to have a comfortable safety margin with respect to hydrogen embrittlement potentials, while the reinforcing steel is sufficiently protected.

Acknowledgement

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