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Maintaining and monitoring durable cathodic protection systems applied on 30 concrete bridges with prestressing steel

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ABSTRACT: This paper describes the experiences of maintenance and monitoring of an innovative project which involves Cathodic Protection (CP) systems which are applied on 30 concrete bridges in the Netherlands. As the concrete beam heads that where protected contain the prestressing anchorages, special care was taken for sufficient protection of the steel without over-protecting any part of the prestressing steel in order to avoid hydrogen embrittlement. The project was executed in 2012 and 2013 and involved a total of over 1.500 prestressed beams heads with a total of more than 3.000 reference electrodes, which will be monitored for 20 years. The organisation for this long-term project was set up to secure a continuing work method so the structures will (safely) be maintained in the coming decades. This organisation, the technical challenges, and results of the maintenance and monitoring of the first two years, which show interesting results with regard to the application of ICCP on prestressed concrete structures, are presented.

1 INTRODUCTION

1.1 *Preface*

This paper describes the experiences of the maintenance and monitoring of an innovative cathodic protection project named 'Liggerkoppen' (which translates to 'beam heads'). The application phase of the project is covered in the paper 'Application of durable cathodic protection systems applied on 30 concrete bridges with prestressing steel' as presented on ICCRRR 2015.

While the long-term processes surrounding the maintenance and monitoring of the Cathodic Protection (CP) systems had to be secured, the innovative solution of adding 20 years of maintenance and monitoring to the contract was established. This paper describes the organizations and the experiences of the maintenance and monitoring phase of this long-term project and the first results from the monitoring of the first 2 years.

1.2 *Paper structure*

Chapter 2 includes, in short, the project history including the preliminary investigations, the damage assessment, and the final choice for cathodic protection as solution for the durability problems. Chapter 3 includes the current project status, the long-term challenges, and a brief description of the applied CP system. Chapter 4 describes the innovative approach of adding 20 years to the contract and the subsequent advantages for all parties involved. Chapter 5 illustrates the technical challenges for the severe amount of data to be obtained and analysed. In chapter 6 and 7 the results of the first period of almost two years of measurements (monitoring) and maintenance are discussed which show interesting results with regard to the application of ICCP on prestressed concrete structures.

2 PROJECT PAST

2.1 *Project cause*

During inspections of various bridges in and over a number of highways the Dutch Highway Administration (DHA: 'Rijkswaterstaat') observed that a significant number of bridges showed severe damage at the ends ('heads') of their beams. Research showed that the cause of this damage was chloride initiated reinforcement corrosion. Because of leakage through the joints the heads of the beams were exposed to desalination salts (containing chloride) and humid conditions. Penetration of chlorides in combination with insufficient concrete cover has initially led to corrosion of mild steel reinforcement and consequential concrete damage. Because of the presence of pretension, usually 3 to

6 prestressing steel bars per beam, the structural risks were considered. Further inspection found that the anchorage showed surface corrosion, fortunately without significant material loss. However, the urgent recommendation was given to stop further corrosion at short notice in order to maintain structural integrity.

2.2 *Solutions*

Rijkswaterstaat, in collaboration with several research offices, designed a principal solution in which the leaking joints were to be replaced to stop the supply of water and chloride contaminated deicing salts.

However, by this measure further corrosion of the reinforcement can not be avoided because of the chloride-contamination of the concrete. The removal of all the contaminated concrete proved to be infeasible because of the anchoring forces of the pre-stressing.

In order to avoid the demolition of the bridges, it was decided to establish a call for tender for the replacement of the expansion joints, removal of damaged concrete of the affected beams over the first meter, and to repair and to provide these areas with CP. While the long-term processes surrounding the maintenance and monitoring of the Cathodic Protection (CP) systems had to be secured, the innovative solution of adding 20 years of maintenance and monitoring to the contract was established.

2.3 *Cathodic protection*

The advise for, and design of, a Impressed Current Cathodic Protection (ICCP) system followed from the demand for the service life of the bridges to be extended with at least 20 years. Therefore, Rijkswaterstaat decided to prescribe an Impressed Current CP system (ICCP) in the tender documents in order to obtain sufficient certainty about the degree of protection. In addition to the replacement of the expansion joints, it was prescribed to apply cathodic protection on the heads (first meter) of the beams which already shown chloride initiated damage and/or chloride contamination and to he the beams which are adjacent.

With the application of the CP system the corrosion of the reinforcement is inhibited to a negligible rate by lowering the potential of the reinforcement. The result is that further degradation and the change of possible failure of the mild and prestressed steel is removed and the concrete repairs will endure much longer than without a CP system.

Because of the greater sustainability and the better opportunities for control and monitoring in the operational phase Rijkswaterstaat decided to select the option of impressed current cathodic protection over a possible galvanic ('sacrificial-anode') system.

Figure 1. As-built CP system with conductive coating and decentralized power supply and monitoring units.

While the beams are prestressed, special precaution was taken in order to avoid possible hydrogen embrittlement ('overprotection') of the prestressed steel bars. Applied on the beams, the CP system has to provide sufficient protection for the steel in order to prevent corrosion, and at the same time overprotection had to be avoided at all times.

2.4 *Impressed current cathodic protection system*

The contract was ultimately awarded to the consortium Mourik—Salverda. After replacing the expansion joints by Salverda, Mourik daughter and CP specialist company Vogel Cathodic Protection started their operation including concrete repair and application of CP at the heads of the selected beams.

Based on the set demands in the tender documents, a CP system was designed based on a conductive coating as anode system. The applied conductive coating consists of a graphite filled aluminosilicate matrix (non cementitious binder) with good strength, adhesion and long term durability when used as an anode. As a primary anode a platinum clad copper wire was used (CuNbPt). Each beam head has its own connection tot the reinforcement steel (since there typically was no electrical continuity between beams). Each beam head was equipped with (2 or 3) reference electrodes for monitoring purposes (Fig. 1).

On the surface near to the mild steel reinforcement an activated titanium decay probe was placed in the original, non-repaired, concrete. For the selection of this location the most likely corroding area was selected as determined by potential mapping. This was typically near the joint, at the bottom side of the beam.

Near the prestressing steel a true reference electrode (silver chloride electrode) with a long lifetime expectancy was placed. For the selection of the electrodes locations the prestressing steel was located on the 'worst case' when considering overprotection risks, so as near to the anode system as possible. On these locations, by drilling towards the cable ducts and continuously measuring the cover thickness in the bore hole (depth probe with concrete cover meter), the reference-electrodes where placed at 10 mm of the prestressing steel. This depth was typically approximately 200 mm, which is also the distance to the anode system. Also 2 connections to the steel were made in every beam by welding in order to provide for a cathodic connection in the CP system of the beam and a second connection for measuring purposes. Cable slots were milled in the concrete surface of the beam in order to make the system more durable, less visible and less vulnerable. All cables outside the surface of the beams are concealed in stainless steel pipes.

The CP system was designed to be operated on solar power with a battery back-up. In the design of capacity, for both the solar power and the battery back-up, the tender documents specified an up-time over 90% on a yearly basis. In effect this means designing for power consumption under poor production circumstances during winter time (The Netherlands is located approximately 51° latitude on the Northern hemisphere).

Furthermore, the tender documents specified the ability for remote control of the CP systems. Due to the large number of reference electrodes there is a strong need to limit the amount of cabling involved by placing power supplies near to each beam. In order to do so, in general 3 beam heads are grouped to a zone (typically 4–5 m^2 of protected surface) with a decentralized, remote controlled power supply.

3 CURRENT PROJECT STATUS

The 'Liggerkoppen'-project was executed in 2012 and 2013 on prestressed beams in 30 concrete bridges of the Dutch Highway Administration (DHA: Rijkswaterstaat) which are spread over 22 locations in the east of the Netherlands.

The number of beams which are equipped/provided with impressed current ('active') cathodic protection varies from merely 3 to over 170 beams per bridge (Fig. 2). In total the project involves an amount of over 1.500 prestressed beams of the total amount of almost 6.000. Every beam is designed as separate 'field' (or pseudo-zone) and contains at least two reference cells (occasionally three cells where placed for evaluation purposes), a titanium 'decay' probe and a 'true reference' cell. This leads to a sum of over 3.000 reference cells, which will be monitored according to the NEN-EN-ISO 12696:2012 Standard.

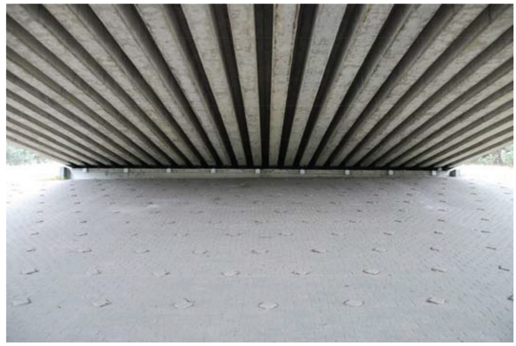

Figure 2. Example of as-built CP system at abutment on 27 beams with 9 decentralized power supply and monitoring units.

While the long-term processes surrounding the maintenance and monitoring of the CP systems had to be secured, the innovative solution of adding 20 years of maintenance and monitoring to the contract was established. As a result of the multi-year contract the structures will (safely) be maintained by the contractor in collaboration with the client in the coming decades.

4 PROJECT ORGANIZATION

During a preliminary assessment of the possible risks and their effect on the function of the CP systems, several key factors of possible failure where determined. These threats are either technical and focus on the system itself, or procedural, due to the organizational challenges for maintaining anything technically complex for a period of 20 years.

The technical threads were dealt with in specifying minimum demands for anode durability, technical provisions for control, and integrated quality control procedures during all phases of the execution and maintenance period. Specific demands where made on the long term performance of the CP system and the monitoring therefore involves at least two depolarisation measurements per year and an annual visual inspection, but with special emphasis on large scale evaluations in year 4, 9 en 14 of the total project. As mentioned, the long-term processes surrounding the maintenance and monitoring of the Cathodic Protection (CP) systems had to be secured. Experiences from Rijkswaterstaat with the application of CP had taught that the involvement of the local administration after execution of the project can decrease rapidly. As a result, the functioning of the CP system was not observed. In the past, this has led to systems that were prematurely disabled or which overtime did not get the attention needed to function as intended. This despite the fact that the regulations like NEN-EN-ISO 12696:2012 prescribe a minimal demand for an annual visual inspection and at least two depolarisation measurements per year.

During a period of 20 years organisations will change, both on the side of the owner (Rijkswaterstaat) and the side of the contractor. While the execution of the work itself can easily be organised in a project based structure, the maintenance and monitoring is a 20 year process having different organisational demands. Special care was taken to avoid the loss of information on the side of Rijkwaterstaat in the transition from 'project' (execution phase) to 'process' (20 year maintenance). This resulted in intensive exchange of information at the end of the execution phase.

Evaluating the execution and transition phase, the assessed risks and threats proved to be valid. Without the attention demanded for the maintenance period following on the execution, this project would easily have become too complex to handle in the 'low attention' phase of 20 years monitoring. At this point, it has been rewarding to see a vital installation being taken care of to function as intended for decades to come.

5 TECHNICAL ASPECTS

As described before; the total project is remotely controlled at 22 locations, including 30 bridges, with CP on 1.500 beam heads, which are spread over 500 zones, and have a total of more than 3.000 reference cells. This will give enormous amounts of data, which have to be acquired, processed, evaluated and reported during a period of 20 years.

Frequently the status of each zone is checked (so-called 'on' measurements), confirming the good operation of the hardware which are especially important due to the fact that these CP systems operate on solar power (Fig. 3). These measurement typically generate data of set voltage, applied voltage, applied current, and the on-potentials of the reference electrodes: typically 4.500 numbers per measurement. Combined with a weekly interval for measuring, this will result in 234.000 numbers per year (4.7 million during the total maintenance period).

In order to establish the fact that no overprotection occurs, another type of measurement (so-called 'instant off' measurement) is performed in which the on-potentials of the individual reference electrodes as well as the behaviour in the instant of shutting off the protective current, in the first second, is measured. This typically results in 33.000 numbers per measurement. Combined with a weekly interval for measuring, this will result in 1.7 million numbers per year (34 million during the total maintenance period).

Figure 3. Central measuring and control unit and solar panels.

To prove sufficient protective current a full depolarisation over a period of 24 hours is performed according to NEN-EN-ISO 12696:2012. Although a minimum of two measurement per year are required in the standard, in the first two years 4 measurements a year are prescribed for this project. Each measurements results in 216.000 numbers, totalling up to 864.000 numbers for the first two years, and 432.000 for the subsequent years (9,5 million during the total maintenance period).

Obviously, the acquisition and processing of the data is challenging and demand automated procedures. Based on automatic processes on a yearly basis all general results are published and statistically treated. Specific measurements that could indicate problems, i.e. failure, insufficient protection or over-protection, are reported without delay on an individual basis. Acceptable outcomes (within bandwidths) are specified in the software to reduce the workload without risking neglect or ignorance of important results.

6 MONITORING

The results of the monitoring during the first two years are promising. All bridges and beam heads show sufficient protection, while no risk of over-protection was observed for this first period.

Typically the initial current density at start up of the zone is very high (50–100 mA/m^2), but drops rapidly to normal values (below 20 mA/m^2). Within a few weeks to not more than 6 months the current density needed for sufficient protection decreases to an average of 1–2 mA/m^2. At the same time this current output requires a steady increase of applied cell voltage (cathode to anode) from an initial 2 volts to values in the range of 3–7 volts. There is a variation between locations, but only minor variations within one bridge. It was therefore decided that, for the time being, all zones within one bridge are operated at the same set voltage.

As a result of the numbers shown above it can be concluded that the apparent system resistance increases. As observed, the instant-off potential at the anode shows a sharp increase from an initial value of 0,2–0,5 volts to values stabilising on approximately 1,8–2,2 volts. Therefore, part of the increase in system resistance is due to semi-permanent polarisation of the anode. Other factors resulting in increased system resistance are assumed to be oxygen consumption and drying out of the concrete after replacing the joints and the application of the conductive coating presenting a barrier to moisture absorption.

Initial measurements of depolarisation show high depolarisations which are well over the minimum requirement of 100 mV according to NEN-EN-ISO 12696:2012, with little variation over beams with active corroding steel and beams included in the project where the protection is more or less preventive (the adjacent beams). Over time this tends to reduce to values from 100–250 mV depolarisation, with no structural difference between protected and prevented sides. This might be due to the repassivation of the active corroding steel, resulting in comparable micro-environments in all beams. The difference between the monitored mild steel reinforcement and the monitored deep locations near the prestressing steel is present at start up, but tends to disappear over time. At some locations there is no significant difference between the behaviour of the reinforcement at typically 35 mm depth and the reinforcement at 200 mm depth. This was unexpected, but shows a deep penetration of sufficient protective current in a heavily reinforced, high quality concrete which is dense, and has a low permeability.

As an example various results are represented in the figures 4 to 6 below. It is noted that some reference electrodes do not meet with the 100 mV depolarisation criterion (criterion 8.6.b from NEN-EN-ISO 12696:2012). Some reference electrodes are dysfunctional, some are placed very deep in order to assess the absence of overprotection at the prestressing steel (up to 40 cm of depth), and some show instant off potentials at very low levels at which depolarisation tends to be too slow

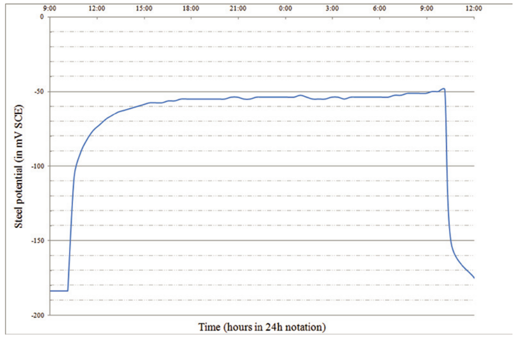

Figure 4. Example cathodic depolarization for a typical viaduct.

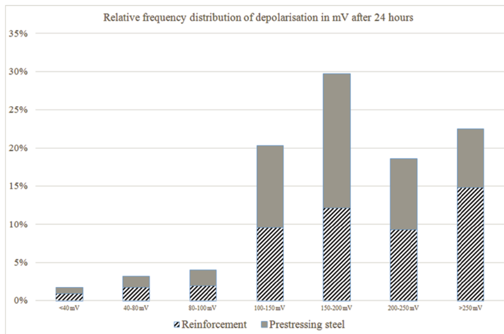

Figure 5. Overall data for frequencies (for degree) of depolarization.

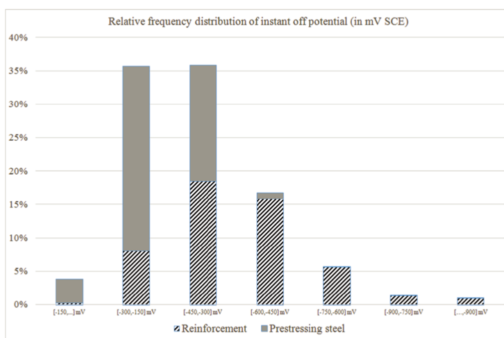

Figure 6. Overall data for frequencies exclusion of hydrogen embrittlement.

to meet criterion 8.6.b but those locations do meet criterion 8.6.a from NEN-EN-ISO 12696:2012. As the number of reference electrodes failing was very small and functional reference electrodes were present at all sites, it was decided not to replace any defective reference electrodes until future maintenance is year 4 or 9.

7 MAINTENANCE

During visual inspections several minor defects from the execution and the maintenance period where detected and dealt with. There are no signs of aging, as expected during this relatively short period, but some evaluated risks have proven to be valid. These observations where related to:

- A single incident of maintenance performed by a third party on a protected site resulted in a few small damages of the conductive coating, some water induced damage on two power supplies and large scale pollution of the surface. These issues where dealt with and resolved.
- At a few locations theft of solar panels and batteries caused temporary shutdown of the systems. After replacement measures were taken to avoid further theft.
- At three locations stainless steel cabled ducts where unintentionally shorted with the anode and corroded as anodes for protecting the reinforcement steel of the abutment beneath the protected beam heads.

All observed problems proved to be self-explanatory and unproblematic to deal with.

Over 10 years of practical experience with the specific conductive coating exists in the Netherlands. At these locations, presently significant signs of aging and failure of the anodes is observed or reported. At the same time there are signs of aging process in specimens subjected to accelerated aging tests in the laboratory. Despite the general expectancy to have a long lasting, durable anode system, within the project described above, some maintenance is expected at the scheduled full scale visual inspections in years 4, 9 and 14. For this purpose the conductive coating is not covered with a top coat, in order to facilitate easy maintenance.

8 PROSPECTIVE AND CONCLUSIONS

Cathodic Protection (CP) is a successful technique to guaranty structural integrity by which corrosion of reinforcement is inhibited to a negligible rate by lowering its potential. In a project named 'Liggerkoppen' (which translates to 'beam heads') 30 concrete bridges in the Netherlands are provided with a Impressed Current Cathodic Protection system. The project was executed in 2012 and 2013 in commissioned by the Dutch Highway Administration ('Rijkswaterstaat'; DHA).

While the long-term processes surrounding the maintenance and monitoring of the CP systems had to be secured, an innovative solution was established which included 20 years of maintenance and monitoring, which will be performed according to NEN-EN-ISO 12696:2012. As a result of the multi-year contract the structures will (safely) be maintained by the contractor in collaboration with the client in the coming decades.

Due to chloride initiated corrosion, caused by leakage through the joints in combination with insufficient concrete cover, numerous beams were damaged and it was urgent to find a solution to stop further corrosion at short notice in order to maintain structural integrity. Distributed over the 30 bridges, a total of over 1.500 prestressed beam heads are provided with a conductive, graphite filled aluminosilicate, coating as anode system.

Each beam head is equipped with (2 or 3) reference electrodes for monitoring purposes, which results in a total of more than 3.000 reference electrodes. Near the prestressing steel a true reference electrode (silver chloride electrode) with a long lifetime expectancy was placed. Special care could therefore be taken for sufficient protection of the steel without overprotecting any part of the prestressing steel in order to avoid hydrogen embrittlement.

Due to the large number of beams per bridge, beam heads were grouped to zones with decentralized power supplies to limit the cabling. The CP systems are powered with solar power with a battery back-up with a up-time over 90% on a yearly basis. The CP-systems are, as tender documents specified, remotely controlled.

During a preliminary assessment of the possible risks and their effect on the function of the CP systems, key factors of possible failure where determined. These threats are either technical, which focus on CP-systems, or procedural, due to the organizational challenges for maintaining anything technically complex for a period of 20 years.

The procedural challenges are dealt with for special care was taken to avoid the loss of information on the side of Rijkwaterstaat in the transition from 'project' (execution phase) to 'process' (20 year maintenance). Evaluating the execution and transition phase, the assessed risks and threats proved to be valid. Without the attention demanded for the maintenance period following on the execution, this project would easily have become too complex to handle in the 'low attention' phase of monitoring. At this point, it has been rewarding to see a vital installation being taken care of to function as intended for decades to come.

The technical threads were dealt with in specifying minimum demands for anode durability, technical provisions for control, and integrated quality control procedures during all phases of the execution and maintenance period. Specific demands where made on the long term performance of the CP system and the monitoring therefore involves at least two depolarisation measurements per year and an annual visual inspection, but with special emphasis on large scale evaluations in year 4, 9 en 14 of the total project.

The status of the zones are frequently monitored, confirming the good operation of the hardware, sufficient protection of the reinforcing steel and the absence of overprotection at the prestressing steel. This results in large sets of data (48 million during the total maintenance period) which have to be processed and evaluated.

The acquisition and processing of the data is challenging and demands automated procedures. Based on automatic processes on a yearly basis all general results are published and statistically treated. Specific measurements that could indicate problems, i.e. failure, insufficient protection or over-protection, are reported without delay on an individual basis. Acceptable outcomes (within bandwidths) are specified in the software to reduce the workload without risking neglect or ignorance of important results.

The results of the monitoring during the first two years are promising. All bridges and beam heads show sufficient protection, while no risk of over-protection was observed for this first period. Typically the initial current density at start up of the zone is very high but drops rapidly to normal values. At the same time this current output requires a steady increase of applied cell voltage (cathode to anode) from an initial 2 volts to values in the range of 3–7 volts. It can be concluded that the apparent system resistance increases.

Initial measurements of depolarisation, to prove sufficient protection, show high depolarisations which are well over the minimum requirement of 100 mV with little variation over beams with active corroding steel and beams included in the project where the protection is more or less preventive. Over time this tends to reduce to values from 100–250 mV depolarisation, with no structural difference between protected and prevented sides. This might be due to the repassivation of the active corroding steel, resulting in comparable micro-environments in all beams. The difference between the monitored mild steel reinforcement and the monitored deep locations near the prestressing steel is present at start up, but tends to disappear over time.

During visual inspections several minor defects from the execution and the maintenance period where detected and dealt with. There are no signs of aging, as expected during this relatively short period, but some evaluated risks have proven to be valid. All observed problems proved to be self-explanatory, were not related to the CP technique itself, and were unproblematic to deal with.

With the application of the CP system the corrosion of the reinforcement is inhibited to a negligible rate by lowering the potential of the reinforcement. The result is that further degradation and the change of possible failure of the mild and prestressed steel is removed and the concrete repairs will endure much longer than without a CP system.