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Application of cathodic protection on 30 concrete bridges with pre-stressing steel: Remaining service life extended with more than 20 years

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ABSTRACT: In view of long term maintenance of its infrastructure facilities the Dutch Highway Administration (Rijkswaterstaat) has repaired over 1.500 heads of prestressed beams and provided them with cathodic protection (CP). The heads of these beams showed moderate to severe damage due to reinforcement corrosion caused by the penetration of chlorides from leaking joints, which required adequate intervention on the short term. By means of cathodic protection the corrosion process has been halted, so that the risk of further degradation of the beams and possible failure of the pre-stressing steel tendons has been minimized. In addition, the concrete repairs in the chloride contaminated parts of the beams will be durable.

1 INTRODUCTION

1.1 *Cause*

Routine inspections of various bridges in and over a number of highways revealed that a significant number of bridges showed serious damage at the ends of the prestressed concrete beams supporting the decks. A large number of these beams exhibited cracks and spalling of the concrete cover as well as rust stains at the end of the beam. It was identified that the bridges affected by this problem were built between 1965 and 1976. The decks of these bridges are supported by so-called prefabricated 'contact-beams', i.e. prestressed concrete T-shaped beams, which were also prestressed as a group in transverse direction. This structural solution results in a bridge deck without necessitating a structural concrete layer on top (Fig. 1).

Further investigations showed that the cause of this damage was reinforcement corrosion initiated by chlorides. Due to leakage through the joints, the heads of the beams were exposed to wet conditions and during winter months to run-off water contaminated by chlorides from de-icing salts. Even though the concrete quality of the prefabricated beams was high, demonstrated by carbonation depths which did not exceed 4 mm, the deep penetration of chlorides combined with a moderate concrete cover thickness (with an average of about 25 mm) had eventually resulted into corrosion of the outer mild steel reinforcement. As a consequence, the concrete cover was spalling, particularly in the corners behind the support blocks and near the anchors of the pre-stressing steel tendons (Fig. 2).

1.2 *Structural risks*

The beams are prestressed with a DYWIDAG system, which consists of 3 to 6 tendons per beam. These tendons are anchored with a steel plate and a nut. Since there was a risk for the pre-stressing system to be corroded, a destructive study was performed by SGS Intron to investigate the condition of the anchors. A part of the concrete behind the anchor was removed by hydro-jetting in order to have a better impression of the effects of corrosion. The results from this inspection showed that the anchors were corroded. However, this was mainly superficial corrosion without significant material loss (Fig. 3).

Figure 1. Typical bridge in the project with 'contact-beams'.

Figure 2. Concrete damage and corrosion of mild steel reinforcement.

Investigations into the structural consequences of the material loss, resulting in a reduction of the concrete and reinforcement section, and of the (mathematical) failure of one of the tendons were conducted by Royal HaskoningDHV. It was concluded that the decrease of the reinforcement cross-section had not resulted in an unsafe structure at the time of inspection, but that further corrosion had to be stopped, in particular to maintain the concrete cover around the pre-stressing anchors and tendons. The computations also showed that for the beams with a limited number of tendons (3 or 4), failure of one of the bars could already lead to the collapse of a beam. Taking into account the serious structural consequences, the urgent recommendation was given to stop further corrosion at short notice and beams with 3 or 4 pre-stressing tendons should be the first to be treated.

1.3 *The solution*

Rijkswaterstaat, in collaboration with TNO, Royal HaskoningDHV and SGS Intron, designed

Figure 3. Surface corrosion of an anchor of a pre-stressing tendon.

a conceptual solution in which the leaking joints were to be replaced to stop the supply of water, contaminated with chlorides in the winter due to the use of de-icing salts.

However, it was clear that with this measure further corrosion of the reinforcement could not be stopped due to the significant levels of chloride contamination already present. The removal of all the contaminated concrete proved to be not feasible because of the anchoring forces of the tendons in the beams at contaminated and damaged areas.

In order to avoid the complete demolition of the bridges, it was decided to start a procurement procedure for the replacement of the expansion joints, the removal of damaged concrete of the selected beams in the affected zone of the first meter from the head of the beam, the repair of the damaged concrete sections with suitable mortars, and to provide these sections with CP of the steel reinforcement (mild steel, tendons and anchors). Part of the design was that beam heads with corrosion damage would be protected and also adjacent beam heads would be provided with CP.

While the long-term processes of maintenance and monitoring of the CP systems had to be secured, the innovative solution of introducing 20 years of maintenance and monitoring explicitly in the contract was established. As a result, the mild steel and the pre-stressing steel will be effectively protected against corrosion for at least 20 years.

Experiences obtained by Rijkswaterstaat with the application of CP on concrete structures during the past 20 years, had learned that the involvement of the local governmental authority after completion of a rehabilitation project can decrease rapidly. As a result, the functioning of the CP system was not checked. In the past, this has led to systems that were prematurely disabled or disconnected or did not seem to work over time. Such situations occurred despite the fact that the regulations (e.g. NEN-EN-ISO 12696) require a minimal demand for a semi-annual electrical test and an annual visual inspection.

Eventually, 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.

2 CATHODIC PROTECTION

2.1 *CP*

Cathodic protection is a technique to inhibit corrosion of steel to a negligible rate by lowering the potential of the metal to be protected. Cathodic protection is divided into galvanic systems (GCP) and systems with impressed current (ICCP).

2.2 *GCP*

In galvanic systems, a sacrificial anode (e.g., zinc or aluminum) is provided, which has a lower rest potential than possible corroding reinforcing steel. The direct coupling of the metallic reinforcement with the less noble anode material results in a galvanic cell in which the anode material goes into solution. In this reaction, electrons are released at the anode which are transported to the reinforcement steel where the iron anodic reaction is inhibited while the cathodic reaction is stimulated.

The advantage of such a system is that it is relatively cheap compared to a CP system with impressed current because there is no requirement for a power source and wiring.

The disadvantage of a galvanic CP system is that in advance it is difficult to accurately predict the extent to which the reinforcement, pre-stressing tendons and anchors will be protected. It is not (easily) possible to control, or to modify, the system after application in order to obtain more or less protection. In addition the anode material is literally consumed as the anodes are sacrificial, making the life span limited.

2.3 *ICCP*

In a CP system with impressed current the reinforcement steel is protected against corrosion using an external power source. Through coupling of the mild steel reinforcement, the pre-stressing tendons and anchors with an external adjustable direct current power supply to an inert anode, a protective current is forced to flow to the steel reinforcement (mild steel, tendons and anchors).

The advantage of such a system is that the level of protection can be controlled by adjusting the voltage or current output.

However, a potential risk of an impressed current system is that it can result in very negative potentials at the steel surface, in particular the prestressing steel. In such a situation so-called 'overprotection' occurs as in the cathodic reaction (very small) hydrogen atoms are formed. These atoms can penetrate the pre-stressing steel and eventually combine to form (much larger) hydrogen molecules. This results in (additional) mechanical stresses in the crystal structure of the pre-stressing steel.

In combination with the already present high mechanical stress levels in the pre-stressing steel, this may lead to brittle failure of pre-stressing steel.

Typically, systems based on impressed current are more expensive than galvanic CP systems. However, impressed current systems are more sustainable and have better options for control and monitoring.

2.4 *Monitoring*

In order to measure the level of protection of the mild steel reinforcement and the pre-stressing tendons, including the anchors, pseudo-reference electrodes (so-called decay probes) were installed in every beam to measure the changes in steel potential. In accordance with NEN-EN-ISO 12696 the reinforcement steel is sufficiently protected if the depolarization of the steel (the shift of the steel potential to more positive values) in the first 24 hours after the (temporary) switch-off of the CP system, is at least 100 mV. Here, with the aid of measuring cells (type activated titanium, Ti*), the depolarization is measured with respect to the so-called "instant-off" potential, i.e. the potential at the steel surface immediately after the switching-off of the applied voltage (Fig. 4).

In order to prevent hydrogen embrittlement of pre-stressing steel every beam is additionally equipped with special measuring cells (type Ag/AgCl) which are placed at the reinforcement or tendons closest to the concrete surface with the applied anode. These ('true reference') cells are stable over time and can be used to measure the absolute potential over a long period of time. In order to prevent hydrogen embrittlement, NEN-EN-ISO 12696 prescribes that the steel potential must always be less negative than -900 mV (with respect to an Ag/AgCl/0.5 M KCl reference electrode).

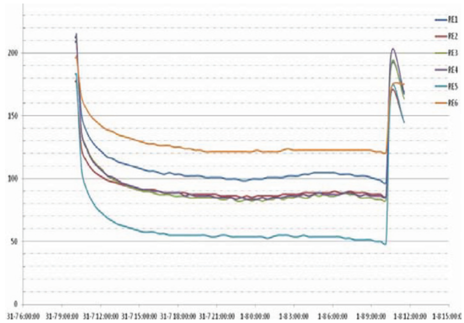

Figure 4. Example of a depolarization measurement (after 1 year of operation).

Figure 5. Severely damaged beam head after removing delaminated concrete.

The challenge for the CP engineer is to find a voltage at which sufficient protective current is supplied to all the steel in the chloride contaminated concrete section in the head of the beam in order to obtain a minimum of 100 mV depolarization in this area, but without the absolute potential at the pre-stressing steel surface to become more negative than -900 mV. At this point the limitation for the absolute potential at the pre-stressing steel surface is leading. In almost every beam equipped with a CP system (98.7%) it was demonstrated at the start-up of the systems that both criteria could be met. At the remaining 1,3% of the beam heads initially depolarization was (a little) less than 100 mV, as otherwise the absolute potential would be too negative at the pre-stressing steel. After some time (1 to 6 months) the current demand of the systems had declined and the voltage was adapted to a level that these beam heads could meet both criteria as well.

3 EXECUTION PHASE

3.1 *Scope and preparations*

The contract was ultimately awarded to the consortium Mourik/Salverda. After replacing the expansion joints by Salverda, Mourik subsidiary and CP specialist company Vogel Cathodic Protection started their operation including concrete repair and application of CP at the heads of the selected beams (starting with a first selection of almost 1.200 beams but in the end resulting in more than 1.500 CP installations on beam heads).

The first step was to remove all loose concrete parts. In some beams it was found that the concrete was affected to such an extent that at the bottom only a pyramid-shaped pressure area directly above the support remained (Fig. 5).

If a large decrease (>10%) of the concrete contact surface area was revealed during restoration of the damage, an assessment of the structural safety was made by Royal HaskoningDHV, after which the beam head was eventually restored in compliance with a prescribed procedure.

3.2 *Repair and installation of CP*

After removal of all delaminated and spalled concrete parts, the reference electrodes (RE's) for monitoring were accurately placed by drilling holes close to either the reinforcement or close to the tendons: 2 (sometimes 3) reference electrodes were placed in every beam (Fig. 6).

In every beam also 2 metallic connections to the steel were made in every beam by welding in order to provide a cathodic connection 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 were concealed in stainless steel pipes.

Next the concrete was repaired with a repair mortar suitable for the application of CP, which generally means without polymers and with an electrical resistivity after hardening comparable with that of the surrounding concrete.

Especially the restricted work space, the deep position of the beam heads at abutments, and the fact that at some locations the execution had to take place at night, complicated the repair work (Fig. 7).

After curing of the repair mortar a conductive coating (the CAST^{3+} system, a 2-component aluminum-silicate polymer filled with carbon) was applied as a (secondary) anode to the concrete surface of the beam head (Fig. 8). In this coating a primary current carrying anode (a CuNbPt-wire) was incorporated.

This type of anode was chosen because of the long-time experience with the material in similar conditions, the durability of the conductive coating in relation to the requested lifetime of 20 years,

Figure 6. Accurately placing the RE's for measuring sufficient protection and avoiding overprotection.

Figure 7. Restricted work space for concrete repair and CP installation.

good practical experience, and the advantages of a conductive coating with regard to the application in the restricted work space between the beam heads. Taking into account this tight working space it was chosen to apply the coating by spraying it on the concrete surface in 2 layers.

The reference electrodes and the connections for both anode (1) and cathode (2) were installed and connected per 2 or 3 beam heads to a decentralized power supply and monitoring unit (Fig. 9).

This unit was connected with a data cable and power cable to the central measuring and control unit (Fig. 10). The decentralized units collect and store the measurement results for the connected beams and these results can be approached, read, collected and programmed remotely through the modem in the central control unit. Furthermore, the voltage applied on the CP system can, depending on the results of the measurements, be adjusted remotely as well, per every decentralized unit (through the modem in the central unit). The data and power cables are concealed in stainless steel pipes.

Figure 8. Applying the conductive coating ($CAST^{3+}$ system).

Figure 9. As-built CP system with 4 decentralized power supply and monitoring units.

Figure 10. CP system with central measuring and control unit and solar panels.

The power of the CP system is, at most locations, provided by a double battery, which is fed by solar panels (Fig. 11). At four locations an exception was made due to the local conditions (shade, buildings, afforestation, pipelines). Here the CP systems are connected to the main electric grid.

Figure 11. Solar panels.

Bridge	Unit	Position	Beams	Reference Electrodes						Potential: 'Instant-Off' value						Depolarization value					
HBS - N - E	1	L28	28/29	Ag	Ag	Ti•	Ag	Ti•		324	265	300	341	281		198	138	119	78	145	
HBS - N - E	2	L26	25/26/27	Ti•	Ag	Ti•	Ag	Ti•	Ag	373	229	301	256	233	278	186	127	201	160	137	139
HBS - N - E	3	L23	22/23/24	Ti•	Ag	Ti•	Ag	Ti•	Ag	260	260	225	226	175	220	148	169	138	149	161	133
HBS - N - E	4	L20	19/20/21	Ti•	Ag	Ti•	Ag	Ti•	Ag	198	225	226	204	219	225	115	135	133	123	101	144
HBS - N - E	5	L17	16/17/18	Ti•	Ag	Ti•	Ag	Ti•	Ag	291	279	371	234	225	248	200	204	264	180	130	164
HBS - N - E	6	L14	13/14/15	Ti•	Ag	Ti•	Ag	Ti•	Ag	258	228	216	229	206	200	158	145	101	116	116	109
HBS - N - E	7	L11	10/11/12	Ti•	Ag	Ti•	Ag	Ti•	Ag	214	184	226	231	221	203	116	113	134	144	121	103
HBS - N - E	8	L8	7/8/9	Ti•	Ag	Ti•	Ag	Ti•	Ag	216	210	213	161	228	206	110	118	121	94	129	118
HBS - N - E	9	L5	4/5/6	Ti•	Ag	Ti•	Ag	Ti•	Ag	185	170	178	180	188	391	94	95	81	90	89	59
HBS - N - E	10	L2	1/2/3	Ti*	Ag	Ti*	Ag	Ti*	Ag	209	179	213	214	184	198	113	93	131	130	135	75

Ti• Ti• - RE   Ag Ag//AgCl - RE

Instant-Off values: results preventing overprotection					
Threshold	Category	Total	Ti*	Ag//AgCl	
150	<150 mV	0	0	0	0%
300	150-300 mV	53	26	27	90%
450	300-450 mV	6	3	3	10%
600	450-600 mV	0	0	0	0%
750	600-750 mV	0	0	0	0%
900	750-900 mV	0	0	0	0%
	>900 mV	0	0	0	0%

Conclusion: No risk of forming hydrogen atoms at the steel surface

Adjustments: *Voltage from 4,0 V → 5,0 V*

Depolarization: results sufficient protection						
Threshold	Category	Total	Ti*	Ag//AgCl	Ti*	Ag//AgCl
40	<40 mV	0	0	0	0%	0%
80	40-80 mV	3	0	3	0%	10%
100	80-100 mV	7	3	4	10%	13%
150	100-150 mV	37	20	17	69%	57%
200	150-200 mV	9	4	5	14%	17%
250	200-250 mV	2	1	1	3%	3%
	>250 mV	1	1	0	3%	0%

Conclusion: In general sufficient depolarization

Figure 12. Example of the survey depolarisation values per bridge.

4 EXPERIENCES AND RESULTS

The first CP systems are now running for over 2 years. The measurements on the CP system illustrate that the reinforcement is well protected, as is confirmed by depolarization values of the Ti*-potential decay probes (≥ 100 mV) (Fig. 12).

Also, the pre-stressing tendons, which receives less protective current due to its deeper position compared to the steel reinforcement, are in general sufficiently protected. This is confirmed by the depolarization values of the Ag/AgCl ('true reference') electrodes. The risk for over-protection, and therefore hydrogen embrittlement, of the pre-stressing steel appears to be nil. In none of the measurements an absolute steel potential ('instant-off' value) is found that exceeds the criterion of –900 mV (the most negative value measured is above, i.e. less negative than, –600 mV).

Lastly, the necessary amount of protective current is found to be relatively small. After the start up of the system, initially a relatively large (protective) current was measured. After a couple of weeks or months the current consumption decreased to approximately 10–30% of the initial starting level. A further reduction is expected as the steel is protected by the CP system for a longer period of time and the conditions surrounding the steel are becoming less corrosive and gradually more steel becomes repassivated.

5 CONCLUSIONS

The execution phase of all 30 bridges within the project was completed in August 2014. The first bridges were completed and commissioned in December 2012.

Severe corrosion of pre-stressing tendons and anchors could, in time, have had major adverse effects on the structural safety of the bridges. With the chosen solution of replacing the leaking joints to create waterproof expansion joints, in order to stop the supply of water and chlorides (de-icing salts), and to protect the reinforcement and pre-stressing steel through cathodic protection, the structural safety of the beams is restored and the remaining service life of the bridges is extended by at least 20 years. With this solution the use of radical reconstruction measures could be avoided.

As the beams are prestressed, special precaution had to be taken in order to avoid the occurrence of hydrogen embrittlement of the pre-stressing tendons. The CP system applied on the beams has to give enough protection to the steel in order to prevent corrosion and at the same time overprotection has to be avoided at all times.

As a result over 3000 reference electrodes were installed in the 1500 beams to assure corrosion protection and avoid hydrogen embrittlement simultaneously. So far with good results.

An aspect of most importance in this consideration is that the owner of the infrastructure (Rijkswaterstaat) has in advance introduced into the contract that the maintenance and monitoring of the CP systems will be performed by the contractor for a period of 20 years.

Because the concrete damage was manifested at a large number of prefabricated beams, it was possible to apply a "standard" approach to a large number of bridges within the project. In principle, the applied approach is suitable for application to similar structures. In view of possible follow-up projects, the operation of the CP systems and the results of the monitoring in the coming years will be critically evaluated.