Impressed current cathodic protection with embedded anodes – field trial on the Viaduc de Saint-Cloud in France

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Abstract. This paper deals with the electrochemical repair of a road bridge, Viaduc de Saint-Cloud which was constructed in the 1970's in France. In 2011, a corrosion analysis was performed together with a durability study. It was demonstrated that the corrosion was induced by chloride ions coming from de-icing salts leaking from the deck. The induced corrosion was increased by the low cover depths resulting in a chloride penetration beyond the reinforcement depth. In order to evaluate the effectiveness and the reliability of Impressed Current Cathodic Protection (ICCP) with embedded anodes, a field trial was performed in 2012 on three span segments including one segment over pier (P2). The results of the ICCP design, the implementation and the monitoring are presented. It was found that two months were necessary before the cathodic protection would reach an equilibrium. Performance criteria as described in ISO 12696 dealing with cathodic protection passed on two segments but failed on the segment over pier. On the latter, where the congestion of reinforcement and prestressed tendons was higher, the anodic system needed some improvement. Finally, the results of the field trial allowed proposing a technical and an economic repair solution.

1 PRESENTATION OF THE BRIDGE

Viaduc de Saint-Cloud was constructed in the 1970s in France (Fig. 1) [1]. It belongs to the A13 highway just west from downtown Paris and allows more than 120000 vehicles per day to cross the River Seine between Saint-Cloud and Boulogne. The span length is 1100 meters. The viaduct is constituted by three-cell box girders (Fig. 2).

Fig. 1. Viaduc de Saint-Cloud (H. Delahousse, Ifsttar).

Fig. 2. Geometry of the segment: three-cell box girders.

2 ASSESSMENT

The bridge assessment was based on visual inspection, concrete durability and reinforcement corrosion investigations.

The results of a visual inspection and delamination survey (rust stains, concrete cracks or spalling damages) were helpful to define different areas from severe to negligible corroded zones. These results are gathered in Fig. 3. The field trial was done on pier P2 which was in a medium to severe state of corrosion and which has easier access (Fig. 4).

Fig. 3. Visual inspection results of the bridge.

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Fig. 4. Field trial on the three segments on pier P2 (from left to right: one segment over pier P2-0 and two span segments P2-1 and P2-2).

Fig. 5 presents the locations of the chloride cores in the segments and the chloride profiles versus concrete depth of the durability investigation [2]. Results show that chlorides have penetrated into the concrete deeper than the reinforcement which was at 10 to 20mm. Chlorides came from de-icing salts that were spread on the bridge in winter and that penetrated the concrete cover leaking through the waterproofing protection and flowing along the segments. It was concluded that the major cause of concrete deterioration was chloride induced corrosion of the steel. Concrete carbonation depth was less than 10mm.

Fig.6 represents the half-cell potential mappings for each segment [3]. From corrosion diagnosis, half-cell potential measurements were in the range 0 to -500mV. The results were consistent with a high probability of corrosion as demonstrated by the gradients in Fig. 6.

3 FIELD TRIAL

3.1 Rehabilitation technique

Classical "patch repair" had failed in 50% of cases after 10 years according to the European ConRepNet Project [4]. The two main causes of failure are debonding between original concrete and new concrete and the incipient anode effect (mainly in the case of chloride contaminated structures) [4, 5]. In the case of the Viaduc de Saint-Cloud this classical repair technique, including removal of contaminated concrete and application of new concrete, was not compatible with the heavy traffic and the structural load capacity of the bridge.

Cathodic protection is the only technology that can directly stop corrosion in reinforced concrete structures if designed, installed, and operated correctly [5-9]. Cathodic protection systems are capable of providing a significantly larger extension in service life depending on the service life of the anode material and the maintenance of the system. In order to address the corrosion problem of the Viaduc de Saint-Cloud, Cathodic Protection rehabilitation treatment was therefore proposed in accordance with NF EN ISO 12696 standard [10].

Fig. 5. Locations of concrete cores (top) and free chloride profiles versus depth on segment P2-0 over pier P2 (medium) and on segment P2-2 (bottom).

Fig. 6. Half-cell potential mappings for the three segments (mV, Cu/CuSO₄)

Within the Cathodic Protection (CP) solutions, the impressed current (IC) technique was chosen rather than using sacrificial anodes (SA) because of the high content of chlorides present in the concrete - even deeper than the reinforcement. ICCP systems arrest steel reinforcement corrosion activity by supplying electrical current from an external source to overcome the ongoing corrosion current in the structure. A number of different anode system configurations are possible but in this case embedded anodes were chosen. They were drilled into the concrete from the interior of the girder offering three main advantages: (i) no traffic interruption, (ii) works could be done by daytime and (iii) no added load to the structure (as would have been the case with a titanium mesh and cementitious overlay).

It is to be noted that ICCP with embedded anodes in France is not a well-known technique and this trial aimed at improving our skills pointing out advantages and limits. The objectives for this research were to:

- Select and design the ICCP system
- Evaluate the performance of the ICCP with embedded anodes for reinforcement and prestressed tendons
- Monitor and control the system
- Establish recommendations for full-scale application

3.2 ICCP with embedded anodes – Design, monitoring and installation

The ICCP system with embedded anodes of the investigated field trial area on the three segments around P2 was designed considering several parameters:

- The surface area of the reinforcement to be protected was calculated for each segment,
- The prestressed tendons that could be in electrical continuity with the reinforcement were also calculated,
- The anodes (CPI) durAnodes (200mm long) or durAfat (50mm long) were made of MMO activated titanium; and were drilled into the concrete (the concrete thickness was around 200mm), and filled with the special compatible CP grout as developed by the anode supplier; locations (heights and depths) depended on the zones to be protected (one or two layers of reinforcement and space) as illustrated with a red cross in Fig. 7.
- The power source (and rectifier) and the targeted current density,
- The reference electrodes were essentially ERE20 (Mn/MnO₂) (Force Technology) or decreased probes (coupons) durAmmo (CPI). Eight reference electrodes per segment were chosen to enable appropriate monitoring and control of the system. They were embedded at different heights and depths in concrete in

order to monitor the behaviour of the reinforcement (one or two layers) and of the post-tensioning tendons. Locations of the reference electrodes are identified with a blue cross in Fig. 7.

- The electronic devices (CPI), comprised a central system unit and three durAcenter slave devices (one for each segment).

Fig. 7 illustrates the zoning arrangement for each segment. It is to be noted that all the prestressed tendons of the three segments were gathered in zone 4 and were monitored with durAcenter 1.

A permanently installed monitoring system allowed us to assess the performance of the cathodic protection based on eight reference electrodes (Mn/MnO₂ type ERE20) per segment (Fig. 7). Remote monitoring was performed using a computer equipped with a modem.

Some pictures of the installation of the ICCP with embedded anodes in the Viaduc de Saint-Cloud are given in Fig. 8. During installation, polarity checks and continuity checks were tested.

3.4 Results

This section describes the findings obtained from the monthly monitoring of the segments over a period of 12 months and discusses in detail the findings.

No half-cell potential mapping was performed after the ICCP system installation as the external segment was repaired with a concrete overlay with a high resistance (to repair spalling and delamination or for aesthetic reasons).

With the monitoring system, output voltages and currents (Fig. 9) and instantaneous OFF steel/concrete potential (Fig. 10) were measured. The performance of the cathodic protection was evaluated based on the second criteria of the NF EN ISO standard 12696 [10]: "a potential decay over a maximum of 24 h of at least 100 mV from Instantaneous OFF". Tab.1 presents the monthly calculated values of the potential decay.

From all these results (Fig. 9, 10 and Table. 1), it can be observed that during the first two months, the performance criteria was not achieved for all the reference electrodes (Tab 1, reference electrodes 1, 3, 4, 5 and 6 for segment P2-0; references 5, 6 and 8 for segment P2-1) and therefore adjustments of the voltage (and thus current) were made as can be observed on Fig.9; Fig. 9 also shows that the currents were higher in spring and summer and lower in autumn and winter.

Fig. 7. Zoning arrangements for the three segments P2-0 (zones 2, 3 and 4), P2-1 (zones 1, 2 and 3) and P2-2 (zones 1, 2 and 3). Size of one segment is 2.2m wide (2m for segment over pier), 5.5m high and 0.2m thick.

Fig. 8. Illustration of the installation of the ICCP system with embedded anodes in the Viaduc de Saint-Cloud.

Fig. 9. Current and voltage measurements during the twelve months trial, segment P2-0 (left) and segment P2-1 (right).

Fig. 10. Instantaneous OFF potential of the eight reference electrodes during the twelve month trial; segment P2-0 (left) and segment P2-1 (right) (the peaks correspond to the monthly verification of depolarisation ISO 12696).

Fig 10 illustrates instantaneous OFF potential of the eight references per segment depending on their locations (segment P2-0: 5, 2 and 1 references respectively in zones 2, 3 and 4; segment P2-1: 3, 1 and 3 references respectively in zones 1, 2 and 3). Zone 4 of Fig 10 left includes the prestressed tendons of the three segments. These latter results also allowed us to verify that there was no risk of hydrogen embrittlement: the green curve relative to the reference located close to the prestressed tendons (zone 4) was not close to the hydrogen risk represented by the dotted line.

After the two months energizing period, the performance was 100% achieved for the three zones of segment P2-2 and segment P2-1 (except for reference electrode 8 but which was not a manganese reference) (Tab. 1). The conclusion was different for the segment over pier P2 (durAcenter 01 in Tab.1). In zone 4 (Ref 1) and zone 2 (Ref 5 only) the performance criteria failed. This result was explained by the presence of the whole prestressed tendons from the three segments in zone 4 and by the presence of concentrated longitudinal and transversal prestressed tendons in zone 2. In order to improve the cathodic protection where larger density of steel was present due to prestressed tendons, a larger anodic surface area was proposed (embedded anodes + ribbon or mesh).

Table 2 summarizes the averaged results obtained after the energizing period for the three segments. The design calculation was made based on an assumption of 15mA/m² of steel surface. The operating currents were in the range 2.1 to 8.8 mA/m² of steel surface. The current per anode per zone was in the range 1.2 to 3.2 mA and was in good agreement with the purchased anodes

(maximum current of 4.4 mA or 3.0 mA respectively for durAnode and durAfat (CPI Denmark)). A life expectancy of more than 25 years was expected.

Table 1. Monthly potential decay values during the twelve months trial for segments P2-0, P2-1 and P2-2 (green colour indicates a pass value whereas orange or red colours a failed value).

Year	2012												2013			
Month	5	6	7	8	9	10	11	12	1	2	3	4				
durAcenter 01 Segment P2-0 (zone 4 including the prestressed tendons of the three segments)																
z4-Ref1	33	27	34	39	37	35	33	29	28	28	27	28	323			
z3-Ref7	344	352	399	381	380	384	362	352	356	312	308	323	170			
z3-Ref8*	170	174	192	189	187	174	172	171	174	177	167	186	204			
z2-Ref2	204	224	259	277	277	280	304	265	287	269	302	285	81			
z2-Ref3	81	86	102	106	118	105	106	102	107	102	100	87	25			
z2-Ref5	25	24	-6	31	37	27	26	12	16	16	16	21	72			
z2-Ref4	72	78	88	102	112	109	112	83	96	65	75	85	82			
z2-Ref6	82	85	91	103	111	107	106	95	97	89	83	86				
durAcenter 02 Segment P2-1																
z3-Ref5	53	44	114	141	146	138	147	133	139	135	135	133	95			
z3-Ref6	95	66	194	221	209	200	202	181	189	191	203	213	120			
z3-Ref7	120	113	194	218	213	190	195	175	181	173	172	186	60			
z3-Ref8*	60	58	89	110	102	81	81	69	70	64	64	76	139			
z2-Ref4*	139	137	154	176	175	152	152	134	138	127	128	138	199			
z1-Ref3	199	206	251	259	258	244	239	228	225	213	215	227	265			
z1-Ref2	265	269	318	323	321	308	301	296	289	290	288	306	162			
z1-Ref1	162	167	211	214	218	211	208	198	202	193	195	199				
durAcenter 03 Segment P2-2																
z3-Ref8	187	214	270	289	302	286	290	282	283	278	282	280	121			
z3-Ref7	121	127	151	164	168	163	165	164	165	163	164	158	82			
z3-Ref6	82	97	121	144	152	144	153	144	152	147	148	139	78			
z3-Ref5	78	78	102	116	119	118	124	123	131	133	127	124	288			
z2-Ref4	288	292	318	330	334	313	315	296	302	293	295	292	310			
z1-Ref3	310	314	375	375	376	360	353	343	342	335	334	334	337			
z1-Ref2	337	346	419	414	416	406	400	395	388	383	382	389	122			
z1-Ref1	122	126	157	159	162	153	149	144	145	146	142	145				
* =durAmmo																

Table 2. Average results for the 10 months period after energizing.

	Segment	Protected zone as designed						Reference electrodes			Average values for results obtained from July 2012 to April 2013				Performance criteria
	Name	Zone number	Location (height of segment)	Concrete surface (m ²)	Steel density (m ² steel /m ² concrete)	Anode type	Number of anode/zone	Ref n°	Number of reference electrode per zone	Depth (cm)	Voltage (V)	Total current/zone (mA)	Current density per zone (mA/m ² steel)	Current per anode/zone (mA)	% month (pass)
durAcenter 01	P2-0/P2-1/P2-2	4	prestressed tendons	1.82	1.75	durAfat	15	1	1	10	7	28	8.8	1.9	0
	P2-0	3	medium	5.14	3.29	durAnode	32	7	2	20	7	93	5.5	2.9	100
								8*		13					100
								2		10					100
	P2-0	2	bottom	5.14	2.41	durAnode	31	3	5	10	7	100	8.1	3.2	90
								5		10					0
								4		10					40-50
								6		10					40-60
	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-
durAcenter 02	*durAcenter 01	4	prestressed tendons	1.82	-	durAfat	(4)	-	-	-	-	-	-	-	-
	P2-1	3	top	1.70	2.27	durAnode	14	5		10					100
								6	4	10	5	35	9.1	2.5	100
								7		10					100
	P2-1	2	medium	1.98	1.51	durAnode	5	8*		8					20
								4*	1	20	5	9	3.0	1.8	100
								3		10					100
	P2-1	1	bottom	6.60	1.00	durAnode	31	2	3	20	5	44	6.7	1.4	100
								1		10					100
durAcenter 03	*durAcenter 01	04	prestressed tendons	-	-	durAfat	(5)	-	-	-	-	-	-	-	-
	P2-2	03	top	1.70	2.23	durAnode	14	8		10					100
								7	4	10	6	30	7.9	2.1	100
								6		10					100
	P2-2	02	medium	1.98	1.47	durAnode	5	5		10					100
								4	1	20	5	6	2.1	1.2	100
								3		20					100
	P2-2	01	bottom	6.60	0.97	durAnode	29	2	3	10	5	39	6.1	1.3	100
								1		20					100

* DurAmmo

4 CONCLUSIONS

Cathodic protection systems are capable of providing a significantly larger extension in service life compared with other corrosion mitigation systems.

In France, to address the chloride induced corrosion of the Viaduc de Saint-Cloud where access and traffic management are challenging, Impressed Current Cathodic Protection with embedded anodes has been tested. In this ICCP system a small current is passed from a permanent anode to the reinforcing steel. It involves the permanent installation of a low voltage, controlled electrical system which passes a direct current to the steel so that the steel is made into a cathode, thus preventing the steel from corroding. The ICCP system was mainly installed from the interior of the bridge, thus allowing significant cost savings without interrupting the traffic which was another advantage. This electrochemical treatment provided protection to the steel that was monitored monthly and controlled over a period of twelve months.

Based on the results of this field trial, the following conclusions were drawn:

- The designed ICCP system was achieving a satisfactory protection for segments P2-1 and P2-2.
- For the segment over pier P2, the ICCP was partly unsuccessful as designed and needed some improvements mainly in the area involving the prestressed tendons,
- For prestressed tendons, the risk of hydrogen embrittlement was not observed. In the areas with large reinforcement density (rebars and prestressed) the field trial has demonstrated the need to increase the value of

the protective current. This could be achieved with the application of a "surface" anode (titanium mesh).

This research provided some technical information to establish recommendations for full-scale application of ICCP with embedded anodes in the Viaduc de Saint-Cloud which counts 518 segments, 16 segments over piers and 16 special segments. It also helped us to acquire technical skills to implement this electrochemical technique and provided financial information for the total cost of repair of the bridge. Finally, it is important to point out that the cost of the field trial only represented 2% of the full-scale repair cost and was therefore worth doing.

It should also be emphasized that people involved in this kind of electrochemical rehabilitation treatment need to acquire sufficient skills to understand how the system works. CP repair therefore needs trained personnel in house or formally certified persons [11].

For future research, the full scale bridge repair should be studied in order to estimate the long term durability of such a treatment and its maintenance.

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