CATHODIC PROTECTION OF PELJEŠAC BRIDGE REINFORCEMENT – IN-DEPTH ANALYSIS OF THE SYSTEM

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Abstract

Corrosion is one of the largest and most common causes of deterioration of reinforced concrete structures in the marine environment. Pelješac bridge is by now a largest reinforced concrete object that is subject to cathodic protection in Croatia. Cathodic protection has been chosen to control corrosion of both carbon steel and stainless steel rebars inside the concrete pile cap element for which, 20 CP units were deployed. Upon the completion of the installation a numerous tests have been conducted to answer many questions on how such massive system works. This paper presents design concepts, installation challenges, and finally deep analysis of the system gotten from the maintenance campaigns.

Keywords: cathodic protection, corrosion control, integrity management, concrete, reinforcement, pile cap, Pelješac bridge, analysis

1 Introduction

Pelješac Bridge is a newly constructed Croatian bridge, whose purpose is to achieve territorial continuity of the Republic of Croatia. Corrosion is one of the largest and most common causes of deterioration of reinforced concrete structures in the marine environment. Newly constructed Pelješac bridge is at the moment largest and most significant project in the homeland whose added value reflects trough the installed cathodic protection system. Cathodic protection has been chosen to control corrosion of both carbon steel and stainless steel rebars inside the concrete pile cap element. Upon the installation of special, concrete tailored metal-metal oxide anodes a preliminary testing was conducted for the purpose of getting an image of cathodic protection efficiency. Protection against corrosion of steel in reinforced concrete constructions and in prestressed constructions is achieved thanks to the alkalinity of the water found in porous concrete. It is known that iron forms a stable oxide layer at high pH values, which protects the metal well from further corrosion. Design deficiencies in the thickness and density of the cover concrete as well as the action of chloride-contaminated electrolytes can cause depassivation and consequently accelerated corrosion. In this case, an additional corrosion protection measure is required. Too porous concrete enables another unwanted phenomenon; chloride attack, resulting in a dangerous form of corrosion, so-called pitting corrosion. It will unfold with the presence of oxygen on the concrete-steel contact surface. Dense low-porosity concrete, well soaked with electrolyte from all sides, will create a high diffusion gradient in its pores, thereby slowing down the flow of oxygen, so that the partial cathodic reaction, will be negligible. If there is no cathodic reaction, the anodic reaction, cannot take place either, and the passivated steel will not corrode.

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However, if part of the reinforced concrete construction is well aerated, the cell is formed; the aerated part becomes predominantly the cathode, and the part where there is a lack of oxygen behaves as an anode, with associated electrochemical reactions.

2 Corrosion destruction models for steel reinforcement inside the concrete

The passivating properties of the aqueous solution found in the concrete pores can be changed by the influence of various factors. There are three important models of corrosion destruction of reinforced concrete: carbonation, chloride attack and corrosion caused by stray currents [1].

2.1 Carbonation

Carbon dioxide from the gaseous or liquid phase penetrates through the pores of the concrete and chemically reacts with $Ca(OH)_2$ in them, thereby reducing the alkalinity. This series of reactions is called carbonation. Carbonation is pronounced for steel reinforced structure exposed to the atmosphere. The concentration of carbon dioxide in soil or water is low. That being said, the level of carbon dioxide can be increased by the decomposition of organic matter present in the soil [1].

2.2 Chloride attack

When the concentration of chloride ions in concrete reaches a value of 0.4% by mass, chloride ions are concentrated on the steel surface forming $Fe(OH)_2$ and $FeCl_2$ [1]. The attack mechanism is as follows:

$$Fe \rightarrow Fe^{2+} + 2e^{-} \tag{1}$$

$$Fe^{2+} + 2Cl^{-} + 4H_2O \rightarrow FeCl_2 \cdot 4H_2O \tag{2}$$

$$FeCl_2 \cdot 4H_2O \rightarrow Fe\left(OH\right)_2 + 2Cl^{-} + 2H^{+} + 2H_2O \tag{3}$$

According to this mechanism, the molecules are located immediately around the anode area, providing back to the anode H^+ and Cl^- ions. Cl^- ions brings new Fe^{2+} ions. It can be seen that the ion does not form corrosion products, nor is it consumed during the corrosion process, but acts as a catalyst.

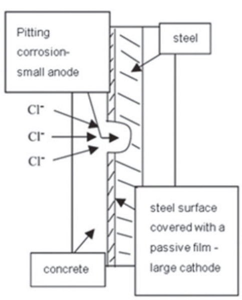

Figure 1 Chloride attack on steel in concrete [1]

Due to the inhomogeneous structure of the concrete itself, the solutions that fill its pores contain a high concentration of chloride ions, which locally destroys the passive film. In this way, the area of steel under the protective layer of the passive film is formed as the cathode, and the attacked part as the anode, which results in the formation of an electrochemical cell, with clearly defined cathode and anode sites (Figures 3 and 4).
There is another way of the negative effect of chloride ions on the corrosion of the structure. Different concentrations of chloride change the electrode potential of the metal, and therefore of the metal construction, and in this way a strong galvanic article is created between two parts of the construction with a different concentration of Cl– ions [2], Figure 5.

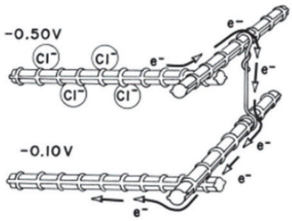

Figure 2 Differences in the concentration of chloride ions create a difference in potential [1]

2.3 Corrosion caused by stray currents

In addition to carbonation and chloride attack, corrosion of steel in concrete can also be caused by stray currents flowing through the concrete structure. Different types of structures can be subject to the passage of stray currents, for example bridges, railway tunnels or buildings located near railways. The passivity of steel in concrete, in addition to being important for protecting the reinforcement from an aggressive environment, is also important for resistance to stray currents.

3 Topology of cathodic protection system for steel reinforcement inside pile caps

Pile cap is steel reinforced concrete element that gathers the piles. It is massive in dimensions; 23.00 m x 29.0 m x 5.0 m 2.5 m and accommodated in the splash zone 2.5 m above and 2.5 m below the water line, hence exposed directly to the chloride ions, Figure 8 and 9 [3].

Figure 3 Pile caps above and below the water line

Main design of the bridge has considered corrosion engineering in its fullest mean providing several interventions to put corrosion under control. These are: increased thickness of concrete protective layer, protective layer reinforcement made of stainless steel (rest is the carbon steel) and impressed current cathodic protection.

Figure 4 Topology of corrosion protection techniques

Cathodic protection system of impressed current type is deployed trough the installation of numerous MMO Ribbon Mesh anodes, shorted in between by titanium conductors. Meshes created this way cover whole side and roof surfaces of each of the 10 pile caps. For the purpose of potential measurement and control permanent reference electrodes type Ag/AgCl 0.5M KCl have been selected and installed according to the design [3]. Finally, TR units, cathodic and anodic distribution boxes finished with variable resistors are installed to complete the impressed current cathodic protection installation.

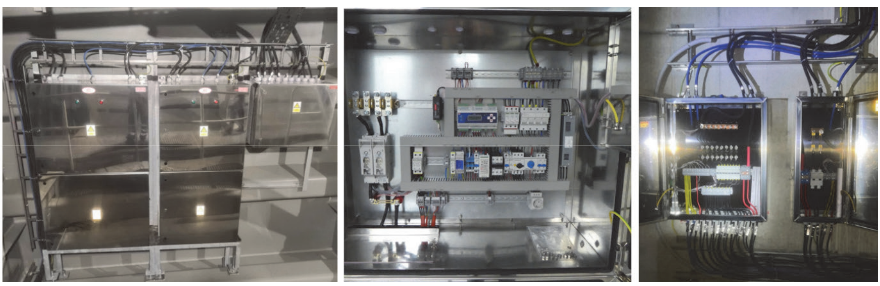

Figure 5 Cathodic protection equipment accommodated inside the pile cap and span structure

4 Measurements prior to the commissioning

Extensive scope of the measurements has been undertaken to get a first image of how such massive CP system might work in the future. Given the above, immediately upon the installation completion a thorough tests have been performed, as per following schedule: steel reinforcement corrosion potential survey (over 10 pile caps), steel reinforcement long-term corrosion potential log (vs. randomly chosen reference electrode), anode functionality test (over 10 pile caps) and corrosion and protection potential mapping of steel reinforcement (over randomly selected raster).

4.1 Corrosion potential survey

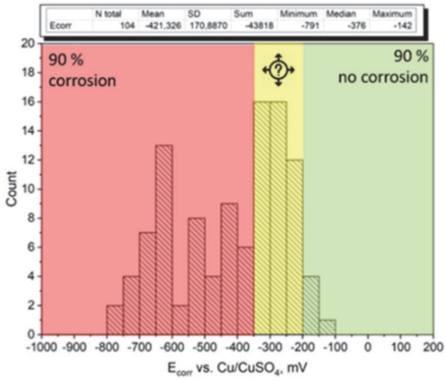

Figure 6 Distribution of corrosion potential values over randomly chosen concrete surface

4.2 Long term corrosion potential log

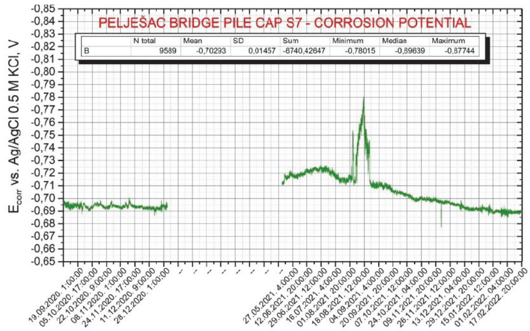

Figure 7 Corrosion potential long-term logging at randomly chosen permanent reference electrode in concrete

4.3 Anode functionality test

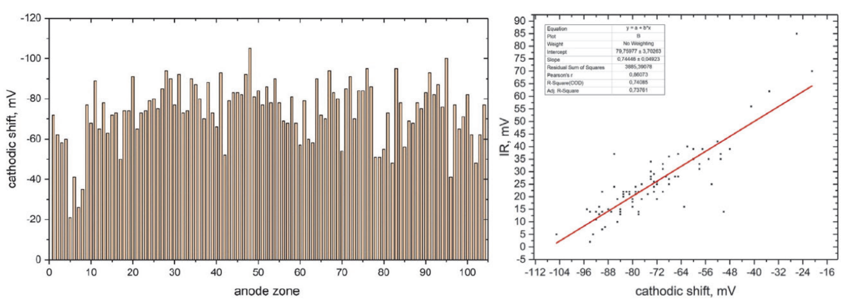

Figure 8 Achieved cathodic shifts as a response to short term constant current injection into each anode zone (left), cathodic shift as a function of IR drop (right)

4.4 Corrosion and protection potential mapping of steel reinforcement

For the purpose of both corrosion and protection potential mapping, a representative and randomly chosen surface raster has been chosen, in overall 104 points.

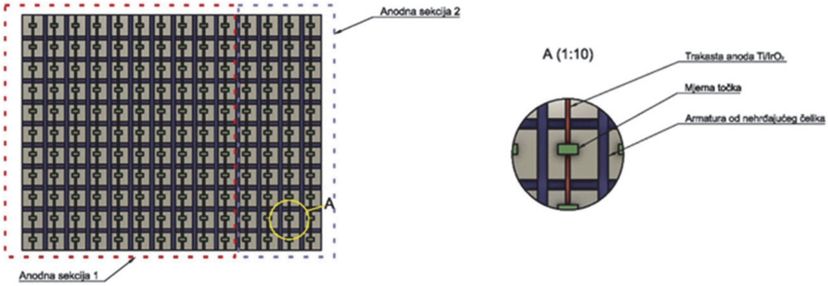

Figure 9 Chosen raster intentionally covers 70% of one anode block and 30% of neighbouring one

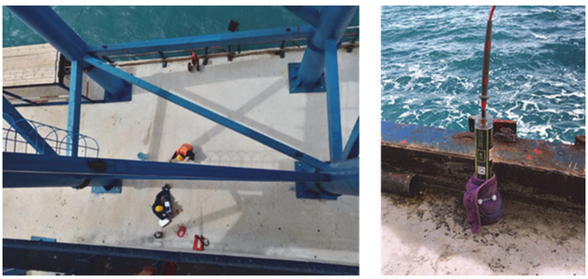

Figure 10 Mapping surface / Reference electrode $Cu/CuSO_4$

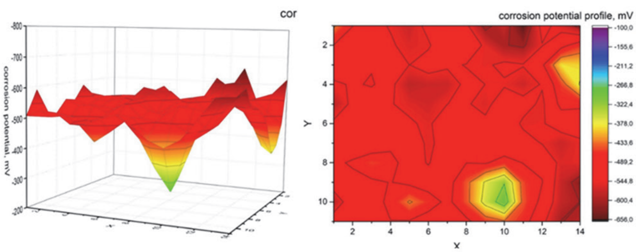

Figure 11 Distribution of corrosion potential

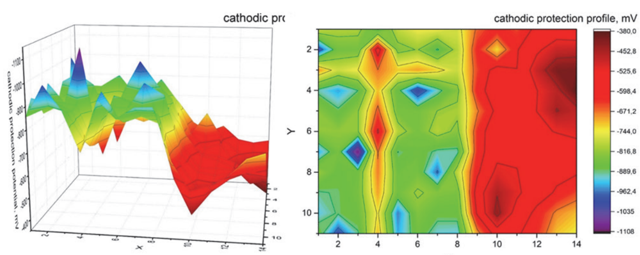

Figure 12 Distribution of polarisation (E_{OFF}) potential

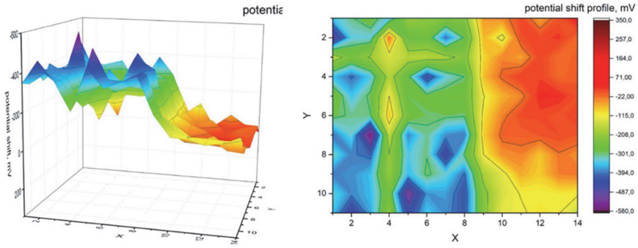

Figure 13 Distribution of potential shifts (E_{OFF}-E_{CORR})

5 Measurements acquired during first year of system maintenance

Among numerous data acquired for the massive system of cathodic protection for 10 pile caps, respectively for 104 anode zones, this paper will present analytics related to the polarisation potential only, which indeed is the most important parameter since it can be commented in a term of protection criterion defined by the relevant standards. In order to get relevant data of pure polarisation potential, as well as voltage shift derived from it, all 20 CP units were subject to synchronised current interruption (Figure 14). Cycle of interruption was selected the way it does not influence the polarisation, having ON cycle significantly longer that OFF one.

Figure 14 Synchronised current interrupters used to simultaneously interrupt all 20 CP units

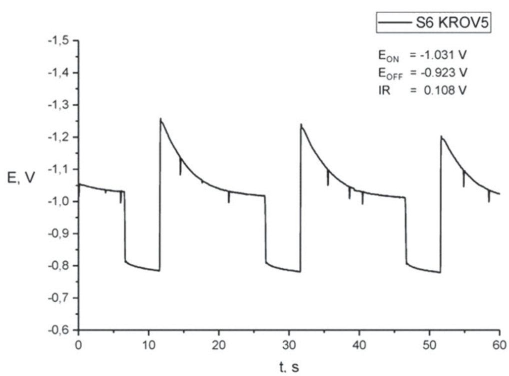

Figure 15 Typical ON/OFF curve with “healthy” polarisation and depolarisation pattern

6 Discussion

Comprehensive analysis of the cathodic protection system implemented for the Pelješac Bridge consisted of both, preliminary testing taken at various construction stages as well as post-installation assessment. The results, as presented in previous sections, not only confirm the theoretical expectations laid out during the design phase but also present some deviations that warrant a deeper exploration to understand their implications on the long-term effectiveness and sustainability of the cathodic protection system.

Corrosion potential mapping survey (figures 9 and 10), organised and deployed with intention to get an authentic and “first” image of condition of reinforcement concreted inside the pile cap revealed uneven distribution and less expected values. Namely, relation between reinforcement and steel (regardless whether it is carbon steel or stainless steel) should be beneficiary for the later, knowing that concrete provides alkaline environment in which steel falls into passivity, therefore exhibiting negligible corrosion rates. Obviously, this is not the case for randomly chosen mapping surface (figures 6 and 11). Majority of corrosion data exhibit active corrosion state with quite uniform distribution. Exemptions are two saddles of passivity, as presented in figure 11. This is and is not strange at the same time; activity of steel right after the installation may be attributed to the chloride contamination of the rebars during construction.

Long term monitoring of corrosion potential on randomly chosen embedded reference electrode shows stability and no major fluctuations, figure 7. Explanation goes in a favour of stable conductivity of the concrete, respectively of no major changes in moisture.

Each anode zone has been initially tested for its functionality, figure 8. Impressing the same amount of current into each geometrically identical anode zone, provided various responses in amount of polarisation of corresponding rebar zone beneath. Dispersion of results is allocated to the various local resistivity conditions.

Following the corrosion potential mapping, mapping of polarisation potential has been deployed for the same reference surface, figures 10 and 12. It is achieved again by impressing certain amount of the current into single anode zone. It is worth emphasizing that reference surface was selected the way it covers 70% of one anode zone and 30% of neighbouring one, figure 9. Polarisation data reveals again dispersion of data and non-uniform distribution of protective current. It means that even inside the relatively small reference surface there are another sub-surfaces with their own differentiation in local resistivity conditions. It is expected over the time to get this profile smoother. Polarisation potential mapping also confirmed no distribution far from the anode, due to the anode-to-cathode proximity (figure 4). This is clear when looking into 30% of surface covered by the non-ignited anode (figure 12 and 13, red area).

Set of measurements deployed after full commissioning and during the regular system operation are numerous and summarized here as a percentage. Graphical and then numerical analysis has revealed system’s major parameters (see typical ON/OFF response for one measuring point, figure 15). The full criterion of cathodic protection shift of 100 mV [4] was achieved at 53% of mandatory measurement points, while at 15% the polarization is mostly significant. At 13% of measuring points no consistent data were collected. The next 20% of points have lower polarization than the corrosion value, therefore this will be subject to further analysis in the upcoming maintenance period. Incomplete polarization is expected considering that the reinforcement in concrete has pronounced capacitive properties and is specific in terms of cathodic polarization. On the other hand, the specificity of concrete as an electrolyte does not allow anode current densities higher than 110 mA/m^2 [5], as such events may lead to the irreversible acidification of the concrete. By continuing the operation of the CP system at limited current values, the double layer will continue with its charging until reaching the complete polarization.

7 Conclusion

Indeed, extensive analysis of cathodic protection system of Pelješac bridge has been performed both prior and after commissioning of the system. Quantity of data extends the scope of this paper; therefore, only main conclusions will be given hereinafter:

- Corrosion potential survey shows variety of values that are in relation with achieved level of steel passivation – they may refer to the corrosion state cause of which cannot be confirmed with certainty, however chloride contamination during construction stage may have taken the role
- Long term corrosion potential log has been acquitted for 1.5 years, showing some fluctuation but no major changes in overall
- Anode functionality test confirmed proper installation and no anode-to-cathode shortages
- System is confirmed to be able to cathodically polarise steel reinforcement, where short term shift values significantly vary
- Ability of polarisation is confirmed by observing the depolarisation pattern
- Linear dependence between cathodic shift and IR drop is confirmed
- After temporary current being injected to one anode block, corresponding surface lifts the potential exclusively towards negative direction, in amount of -50 to -500 mV
- Thermodynamically, this shift moves steel from corrosively active state to the state of immunity
- Even though distribution is uneven, expected is stabilisation over the time
- Current injected to selected anode block does not spread much around (close anode-cathode proximity)
- Maintenance data during first year of normal operation of the system revealed that the full criterion of cathodic protection shift of 100 mV [4] was achieved at 53% of mandatory measurement points, while at 15% the polarization is mostly significant; 13% of measuring points provided no consistent data; 20% of points have lower polarization than the corrosion value therefore this will be a subject of further analysis in the upcoming maintenance period

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