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PROTECTION OF BRIDGES AGAINST STRAY CURRENT CORROSION

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Abstract. A case study of Siennicki Bridge stray current corrosion hazard is presented. A corrosion risk was caused by incorrectly designed tram line traction which goes over the bridge. No dielectric insulation between running rails and bridge steel construction was used. A variety of protection methods against stray currents are described. Characteristics of the endangered bridge were described. Impressed current cathodic protection system against stray currents was proposed and designed at the Department of Electrochemistry, Corrosion and Materials Engineering, Gdansk University of Technology. Coupon technique measurements and potential measurements were performed to verify the effectiveness of the protection system.

Keywords: steel bridge, reinforced concrete, corrosion, stray current, cathodic protection.

1. Introduction

Constructions made of metal and reinforced concrete are susceptible to corrosion hazards (Akiyama *et al.* 2012; Ellingwood 2005). One can prevent corrosion by application of corrosion protection systems which address factors responsible for corrosion. For instance: metal constructions that are susceptible to environmental corrosion are protected by coatings (Damgaard *et al.* 2010), protection of underground and immersed metal constructions is carried out by combination of coatings and cathodic protection (Gan *et al.* 1994). Reinforced concrete steel bars can be protected with cathodic protection systems (Bertolini *et al.* 2004; Brown, Sharp 2008). New concrete has high pH, thus steel reinforcements are in the passive state and they do not corrode (Glass *et al.* 1997). The corrosion rate of a metal depends on its potential in the surrounding electrolytic environment and it decreases when the potential is changed to a more negative one (Nygaard, Geiker 2012; Yamashita *et al.* 1998).

When cathodic protection is applied a corrosion reaction is hindered. It is attained by decreasing the electrochemical potential of the protected construction with a direct current that flows from an anode through electrolytic environment to the surface of the protected metal (Bertolini *et al.* 1998). A direct current that flows to the metal through environment/metal interface lowers the electrochemical potential of the metal. Such a phenomenon is referred as Cathodic Protection (CP). Cathodic protection can be carried out in two ways. One can create a galvanic couple on purpose – by connecting sacrificial anodes to the protected constructions (Szabo, Bakos 2006a). Those anodes are made of alloys which have lower electrochemical potential than the metal the metallic construction is made of. The second method utilizes an Impressed Current Cathodic Protection (ICCP) source (ICCP system) which is connected to the construction and to auxiliary anodes (Szabo, Bakos 2006b). In both cases only cathodic reactions occur on the surface of the protected construction and anodic reactions occur on the anodes surface. Sacrificial anodes are usually made of magnesium, zinc or aluminium alloys (Radosevic *et al.* 2007). They supply the protective current, however they also dissolve. Thus sacrificial anodes have to be replaced. ICCP anodes are made of materials that are very hard to dissolve (i.e. high silicon cast iron) or insoluble materials (i.e. platinized titanium) in order to provide the longest operating time possible.

Corrosion hazards of bridges are well known (Augonis *et al.* 2012; Coca *et al.* 2011; Fuhr, Huston 1998). Atmospheric corrosion, strain corrosion and fatigue corrosion phenomena are considered when the construction is being designed (Kossakowski 2013). Corrosion resistant materials are chosen and protective coating systems are applied. In some cases there can be a dangerous corrosion factor that has to be addressed and extraordinary measures have to be taken. Direct current tram railway tractions are a very common source of stray currents (Tzeng, Lee 2010). Stray currents leak from tram rails to the electrolytic environment – for instance earth, wet concrete and water. Stray

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currents flow to the negative terminal of the tram substation. They can flow through metal constructions on their way back to the source (Darowicki, Zakowski 2004; Zakowski 2009). A current that flows out of the construction to the electrolyte causes the corrosion hazard (Zakowski, Darowicki 2000) – the anodic polarization of the construction and electrolytic corrosion take place.

Stray Current Corrosion (SCC) protection methods can be categorized as active and passive ones. Passive ones reduce the current leakage from the tram traction. Thus, one can weld rails together, repair rail connectors, place rails on sleepers (in order to reduce rail-round contact), reduce any undesired electric contact between railways and nearby metal constructions. Active methods are classified as cathodic protection methods. Their purpose is to reduce or eliminate stray currents flow from the endangered construction to the electrolytic environment through the metal-electrolyte phase boundary. Such effect can be achieved by the application of the electrical drainage, cathodic protection with the impressed current source or by grounding electrodes through which the current can flow out of the construction. The most commonly used method is the installation of electrical drainage (Machczynski 2002). It involves creating the electrical connection between the endangered construction and rails by an electric cable. Thus stray currents leave the construction through the cable instead of metal/electrolyte interface. Corrosion reactions do not occur at the metal surface. In the proximity of the rail traction the voltage between the metal construction and rails often changes its sign (Zakowski, Sokolski 1999). In order to ensure that the current can only flow from the construction to traction rails a diode is installed in the drainage system (it is called unidirectional drainage bond). In case of the reversed polarization the diode prevents the current flow from rails to the construction through the cable. Cathodic protection with the impressed current source is installed when it is possible to compensate stray currents intensity and to polarize the construction in order to reduce corrosion rate. Grounding electrodes create a low resistance connection between the construction and the electrolytic environment. They reduce the current flow through the metal/electrolyte interface and create an easy electric path. Thus, the electrolytic corrosion rate is reduced.

Fig. 1. Siennicki Bridge in Gdansk

2. Description of the steel bridge hazard – case study

Siennicki Bridge is located in Gdansk, Poland, over the Dead Wisla River. It connects the city with the Port Island. It was opened for the first time in 1912. It used to be a drawbridge construction. In 1927, the tramway line across the bridge was built. The bridge was heavily damaged during the Second World War.

The last renovation was carried out in 1990. The bridge is a welded construction made of 18G2A steel. It has one span which is supported by pillars and two bridgeheads. It is approx 96 m long. An image of the bridge is presented in Fig. 1. Old pillars and bridgeheads were adapted to fit the new span. During the general overhaul only the above-water body was rebuilt and consolidated. Pillars and bridgeheads are placed on the old timber pile construction. Their underwater facing is made of stone bonded with cement mortar. During the renovation embrittled parts of the bridge were removed and replaced with reinforced concrete. The bridgeheads were adjusted to fit the span design and there were spherical bearings installed. The bridge pavement is a three layer structure: mastic 1 cm thick, asphaltic concrete 15 cm thick and asphaltic concrete top layer 4 cm thick.

There was the tram track installed over the bridge. Rails were placed in steel channels and fastened to the steel plate of the bridge with bolts. Thus it was not possible to electrically insulate tram rails and the bridge steel pavement. Such state is inconsistent with the European standard *EN-50162:2004 Protection against Corrosion by Stray Current from Direct Current Systems*. In the 7.6 point of this standard it is recommended that stray currents outflow and their influence on nearby constructions have to be minimized. Separation of the traction return circuit from pipelines, cables, bridges and tunnels is recommended by this standard. The direct metallic connection causes stray currents outflow from the tram line system. They flow directly from tram rails through the bridge causing the stray current corrosion phenomenon at the place where the current leaves the metallic elements of supporting construction. Affected parts in the case of the Siennicki Bridge are two bridgeheads and bridge supports made of reinforced concrete. Thus the metallic connection between bridge and rails is an upset which causes SCC threat. Bridge administrator decided to take measures in order to prevent the SCC phenomenon.

3. Application of stray current protection system

In order to assure construction safety a stray current corrosion protection system was designed at Department of Electrochemistry, Corrosion and Materials Engineering, Gdansk University of Technology. The system was designed with this particular Siennicki Bridge case in mind. The tram traction construction precluded application of the electrical drainage. The cathodic protection system with the impressed current source was applied. Pre-design measurements and test cathodic polarization were performed. Bridge potential distribution was investigated. It was found that a satisfying stray current protection was reached with one CP station. Anodes were placed at the riverside. The protection current demand was approx 20 A. Cathodic protection system circuit consisted of: cathodic protection station, electrical power supply line, multi-anode groundbed, anode cap and cable, cathode cap and cable. Test and verification circuit consisted of: permanent zinc reference electrodes, pilot Cu/CuSO$_4$ electrode, potential cap and cable, remote control system, anode test station. A simplified scheme of the protection system and its elements placement is shown in Fig. 2. Orientation of the bridge in Figs 1–2 are complaint.

The cathodic protection installation was placed on the left side of the bridge (from Fig. 1 point of view). Parameters of the cathodic protection station were as follows: adjustable current intensity up to 30 A at the maximum output voltage of 40 V. The cathodic protection system was supplied from the bridge electric lighting system. The groundbed was designed as a group of four anodes ϕ50×2000 mm made of high silicon cast iron. Anodes were buried and placed in a graphite-coke backfill in order to lower the current spread resistance. The groundbed was localized approx 50 m away from the bridge. The anode spread resistance equalled 2.15 Ω. Cable YKOXs 1×16 mm^2 (shipboard power cable with cross-linked polyethylene insulation and PVC sheath) connecting CP station to anodes was buried in soil. The cathode cap was made by connecting the cable (YKOXs 1×16 mm^2) from CP station to the steel span of the bridge. Pilot electrode – saturated Cu/CuSO$_4$ electrode of a cylindrical shape (110 mm×250 mm) was connected to the CP station with a buried cable (YKOXs 1×4 mm^2).

In order to inspect the efficiency of the cathodic protection a system consisting of 12 underground zinc reference electrodes was designed. It enabled measurements of bridge potential distribution along its length. A distant reading equipment utilizing the telephone line connection was used to monitor the working parameters of the protection system.

4. Effectiveness of applied protection system

After the start-up of the cathodic protection system the current intensity equalled to 16 A. This resulted mainly from the anode resistance and operating voltage of cathodic protection station. It was a value slightly lower than the current demand determined in the pre-design measurement process. Effectiveness of the cathodic protection system was evaluated by coupon weight loss technique (Khan 2004) and measurements of the bridge potential shift caused by the cathodic protection current.

Gravimetric measurements of steel coupons weight loss were performed. Coupons were connected to the bridge span, simulating exposed bridge elements. There were coupons exposed prior and after installation of the cathodic protection system. Corrosion rates were calculated and averaged 0.139 mm/year and 0.039 mm/year respectively for coupons exposed before and after the cathodic protection system were installed. The corrosion rate of the bridge was reduced to the level which is acceptable for constructions endangered by stray currents (Hosokawa *et al.* 2004). Thus, it was proven that the cathodic protection system was fully functional and corrosion rates were significantly lowered. It has to be noted that coupon technique gives the most reliable results if the duration of the exposition is sufficient.

Exemplary registers fragment of bridge potential E_{zn} measured against one of the zinc reference electrodes,

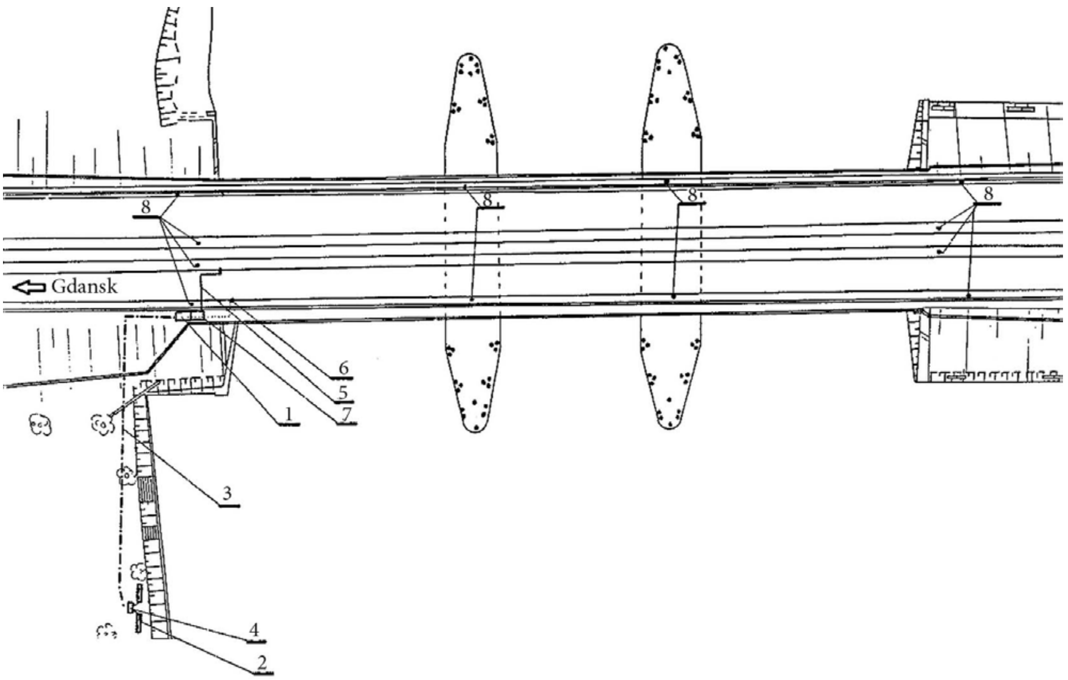

Fig. 2. Simplified scheme of Siennicki Bridge: 1 – cathodic protection station; 2 – multi-anode groundbed; 3 – anode cable; 4 – anode test station; 5 – cathode cable; 6 – potential cap; 7 – remote control system; 8 – permanent zinc reference electrodes

which was placed near the left bridgehead, is presented in Fig. 3. There are plots where protection current is turned on and off. Quick potential shifts are typical for the interaction of dynamic stray currents which originate from the tram traction (Zakowski, Darowicki 2003). When the cathodic protection current was switched on the bridge average daily potential was lowered by about 80 mV. This fact indirectly indicates that the corrosion rate of bridge metal elements was hindered.

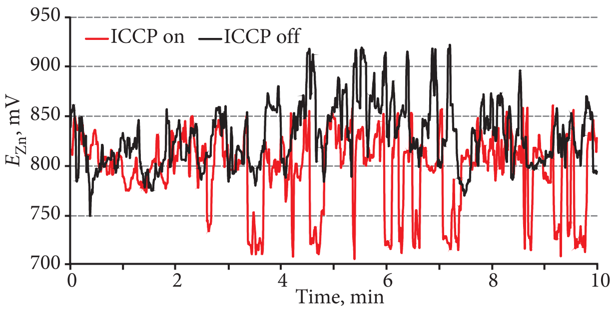

Fig. 3. An example of bridge potential changes

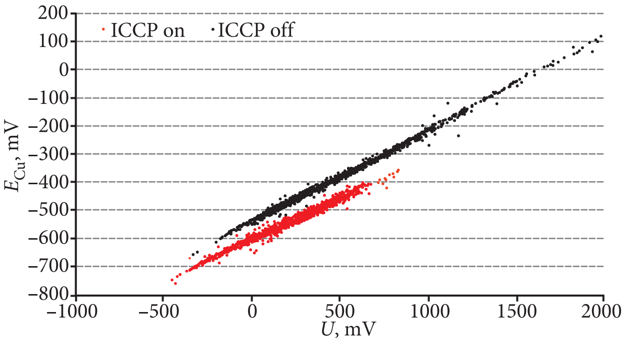

Fig. 4. Potential–voltage correlation spectra measured at the left bridgehead

Furthermore, a correlation plot has been plotted for a relationship between the stray current electric field vector in soil and the bridge potential (Fig. 4). The electric field vector U was measured between two zinc electrodes, the bridge potential E_{Cu} was measured against a portable saturated copper reference electrode. The upper spectra in Fig. 4 corresponds to the ICCP turned off, the lower spectra to the ICCP turned on. The protection effect is visible as the downward shift of the spectra.

Spatial bridge potential distributions and potential contour maps are presented in Fig. 5. Both cases of the cathodic protection current: turned on and off are presented. Data was acquired from 30 minutes-long potential measurements. The bridge potential was measured simultaneously against all of buried zinc electrodes. Data was plotted in agreement with the following procedure:

- an average bridge potential value against every buried electrode was calculated;
- a spatial localization of every electrode was specified in a two-dimensional '*XY*' coordinate system;
- every point in the '*XY*' plane corresponding to the electrode placement was given a '*Z*' variable value, which equals to the calculated average potential value;
- the variable '*Z*' was interpolated for the whole '*XY*' plane. Thus the bridge potential spatial distribution for the whole plane was calculated;
- two-dimensional potential distribution maps were obtained by projection of the variable '*Z*' on the '*XY*' plane. Isolines connect points of the same potential value.

The left diagram in the Fig. 5 indicates that without the cathodic protection the bridge potential was higher at the right bridgehead. It implies that the anodic polarization of the structure was greater there. This phenomenon was caused by greater stray current density outflow from

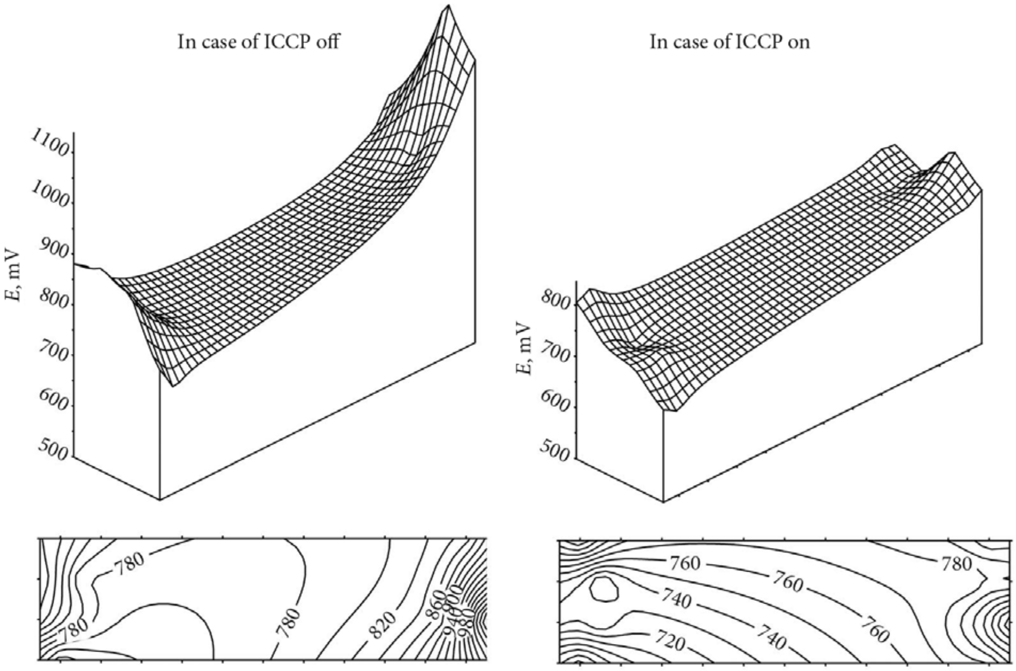

Fig. 5. Potential distributions of the bridge

the bridge metal parts to the environment. Thus the stray current corrosion hazard was graver at the region of the right bridgehead. Such a potential distribution was caused by the tram substation location. It was located few kilometres away to the right from the bridge. Stray currents flowing out from the bridge tend to flow in the substation direction. When the cathodic protection station was turned on the steepness of the potential distribution surface lowered and the average potential value was also lowered.

Thus, the effect of the ICCP system was the lower value of the bridge potential. The left and the right bridgehead potential were lowered by approx 80 mV and 200 mV, respectively. The protection effect was satisfying. Almost the whole bridge construction met the 100 mV polarization criterion requirement which is given in the European standards *EN-12696:2000 Cathodic Protection of Steel in Concrete* and *EN-14505:2005 Cathodic Protection of Complex Structures.* The magnitude of the potential shift indicates that the cathodic current of greater intensity flew through the right bridgehead. It also indirectly indicates that the spread resistance at the right bridgehead is lower compared to the left bridgehead.

5. Conclusions

1. Protection of metallic supporting construction of bridge against stray currents is possible with the impressed current cathodic protection. Corrosion protection system of Siennicki Bridge presented in this article is an example of such a case. Source of corrosion hazard has been identified and a proper protection system was chosen.

2. The impressed current cathodic protection system was designed for the Siennicki Bridge. The system's efficiency was verified by application of corrosion coupon technique and potential investigations. Performed measurements proved the system's sufficiency.

3. In certain situations bridges are susceptible to electrolytic corrosion which is caused by stray currents interference.

4. Elimination of stray current corrosion is only possible by application of electrochemical protection. In every case the reason of the stray current interference has to be identified and the adequate protective method has to be implemented.

5. Civil engineers and contractors must be aware of corrosion risks. Both design and workmanship flaws have to be eliminated; in the described case – the bolt connection between tram rails and bridge span and absence of dielectric insulation are unacceptable.

References

Akiyama, M.; Frangopol, D. M.; Suzuki, M. 2012. Integration of the Effects of Airborne Chlorides into Reliability-Based Durability Design of Reinforced Concrete Structures in a Marine Environment, *Structure and Infrastructure Engineering* 8(2): 125–134. http://dx.doi.org/10.1080/15732470903363313

Augonis, M.; Zadlauskas, S.; Rudzionis, Z.; Pakalnis, A. 2012. The Analysis of Reinforced Concrete Box Girder Viaduct Defects and Their Estimation, *The Baltic Journal of Road and Bridge Engineering* 7(1): 13–21. http://dx.doi.org/10.3846/bjrbe.2012.02

Bertolini, L.; Bolzoni, F.; Pastore, T.; Pedeferria, P. 2004. Effectiveness of a Conductive Cementitious Mortar Anode for Cathodic Protection of Steel in Concrete, *Cement and Concrete Research* 34(4): 681–694. http://dx.doi.org/10.1016/j.cemconres.2003.10.018

Bertolini, L.; Bolzoni, F.; Pedeferri, P.; Lazzari, L.; Pastore, T. 1998. Cathodic Protection and Cathodic Prevention in Concrete: Principles and Applications, *Journal of Applied Electrochemistry* 28(12): 1321–1331. http://dx.doi.org/10.1023/A:1003404428827

Brown, M. C.; Sharp, S. R. 2008. Survey of Cathodic Protection Systems on Virginia Bridges, *Transportation Research Record* 2044: 61–67. http://dx.doi.org/10.3141/2044-07

Coca, O. F. J.; Tello, M. U. L; Gaona-Tiburcio, C.; Romero, J. A.; Martínez-Villafañe, A.; Maldonado, E.; Almeraya-Calderón, F. 2011. Corrosion Fatigue of Road Bridges: a Review, *International Journal of Electrochemical Science* 6(8): 3438–3451.

Damgaard, N.; Walbridge, S.; Hansson, C.; Yeung, J. 2010. Corrosion Protection and Assessment of Weathering Steel Highway Structures, *Journal of Constructional Steel Research* 66(10): 1174–1185. http://dx.doi.org/10.1016/j.jcsr.2010.04.012

Darowicki, K.; Zakowski, K. 2004. A New Time-Frequency Detection Method of Stray Current Field Interference on Metal Structures, *Corrosion Science* 46(5): 1061–1070. http://dx.doi.org/10.1016/j.corsci.2003.09.007

Ellingwood, B. R. 2005. Risk-Informed Condition Assessment of Civil Infrastructure: State of Practice and Research Issues, *Structure and Infrastructure Engineering* 1(1): 7–18. http://dx.doi.org/10.1080/15732470412331289341

Fuhr, P. L.; Huston, D. R. 1998. Corrosion Detection in Reinforced Concrete Roadways and Bridges via Embedded Fiber Optic Sensors, *Smart Materials and Structures* 7(2): 217–228. http://dx.doi.org/10.1088/0964-1726/7/2/009

Gan, F.; Sun, Z. W.; Sabde, G.; Chin, D. T. 1994. Cathodic Protection to Mitigate External Corrosion of Underground Steel Pipe Beneath Disbanded Coating, *Corrosion* 50(10): 804–816. http://dx.doi.org/10.5006/1.3293470

Glass, G. K.; Hassanein, A. M.; Buenfeld, N. R. 1997. Monitoring the Passivation of Steel in Concrete Induced by Cathodic Protection, *Corrosion Science* 39(8): 1451–1458. http://dx.doi.org/10.1016/S0010-938X(97)00051-6

Hosokawa, Y.; Kajiyama, F.; Nakamura, Y. 2004. New Cathodic Protection Criteria Based on Direct and Alternating Current Densities Measured Using Coupons and Their Application to Modern Steel Pipelines, *Corrosion* 60(3): 304–312. http://dx.doi.org/10.5006/1.3287735

Khan, N. A. 2004. Using Coupons and ER Soil Corrosion Probes in Applying Pipeline CP Criteria, *Materials Performance* 46(4): 26–30.

Kossakowski, P. G. 2013. Fatigue Strength of an over One Hundred Year Old Railway Bridge, *The Baltic Journal of Road and Bridge Engineering* 8(3): 166–173. http://dx.doi.org/10.3846/bjrbe.2013.21

Machczynski, W. 2002. Simulation Model for Drainage Protection of Earth-Return Circuits Laid in Stray Currents Area, *Electrical Engineering* 84(3): 165–172. http://dx.doi.org/10.1007/s00202-002-0119-5

Nygaard, P. V.; Geiker, M. R. 2012. Measuring the Corrosion Rate of Steel in Concrete – Effect of Measurement Technique, Polarisation Time and Current, *Materials and Corrosion* 63(3): 200–214. http://dx.doi.org/10.1002/maco.201005792

Radosevic, J.; Kliskic, M.; Gudic, S.; Smoljko, I.; Vrsalovic, L. 2007. Some New Studies of Sacrificial Anodes, *Corrosion Reviews* 25(1–2): 1–11. http://dx.doi.org/10.1515/CORRREV.2007.25.1-2.1

Szabo, S.; Bakos, I. 2006a. Cathodic Protection with Sacrificial Anodes, *Corrosion Reviews* 24(3–4): 231–280.

Szabo, S.; Bakos, I. 2006b. Impressed Current Cathodic Protection, *Corrosion Reviews* 24(1–2): 39–62.

Tzeng, Y. S.; Lee, C. H. 2010. Analysis of Rail Potential and Stray Currents in a Direct-Current Transit System, *IEEE Transactions on Power Delivery* 25(3): 1516–1525. http://dx.doi.org/10.1109/TPWRD.2010.2040631

Yamashita, M.; Nagano, H.; Oriani, R. A. 1998. Dependence of Corrosion Potential and Corrosion Rate of a Low-Alloy Steel upon Depth of Aqueous Solution, *Corrosion Science* 40(9): 1447–1453. http://dx.doi.org/10.1016/S0010-938X(98)00041-9

Zakowski, K. 2009. The Determination and Identification of Stray Current Source Influences on Buried Pipelines Using Time/Frequency Analysis, *Anti-Corrosion Methods and Materials* 56(6): 330–333. http://dx.doi.org/10.1108/00035590911000313

Zakowski, K.; Darowicki, K. 2003. Potential Changes in an Electric Field and Electrolytic Corrosion, *Anti-Corrosion Methods and Materials* 50(1): 25–33. http://dx.doi.org/10.1108/00035590310456261

Zakowski, K.; Darowicki, K. 2000. Methods of Evaluation of the Corrosion Hazard Caused by Stray Currents to Metal Structures Containing Aggressive Media, *Polish Journal of Environmental Studies* 9(4): 237–241.

Zakowski, K.; Sokolski, W. 1999. 24-hour Characteristic of Interaction on Pipelines of Stray Currents Leaking from Tram Tractions, *Corrosion Science* 41(11): 2099–2111. http://dx.doi.org/10.1016/S0010-938X(99)00034-7

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