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Service life and life cycle cost modelling of cathodic protection systems for concrete structures

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ABSTRACT

Cathodic protection (CP) of reinforcing steel has been applied successfully to concrete structures with corrosion damage for more than 25 years. Performance and maintenance data are reported from an inventory of CP systems in The Netherlands installed on about 100 structures between 1987 and 2010. The large majority provides corrosion protection for a long time. Degradation of components and overall systems seems to occur in limited numbers. Failure of components and total systems as a function of age is quantified. On the average, the time until minor repairs of parts is necessary is about 15 years. Global failure of the anode, which necessitates near complete replacement of the system, is rare. Based on the statistical analysis of field data, the cost of maintaining a CP system is predicted using a life cycle cost model.

1. Introduction

Corrosion of reinforcing steel in concrete structures may occur, e.g. in bridges due to penetration of chloride ions from de-icing salts or sea water spray [1]. Reinforcement corrosion causes concrete cracking and steel diameter reduction, eventually resulting in loss of safety. Conventional repair means heavy, labour intensive and costly work. Economic pressures work against the required quality level (proper cleaning of reinforcement, removal of contaminated concrete). Consequently, conventional repair is short lived in many cases. Corrosion reappears quickly and structures need to be repaired again after a relatively short time, further increasing life-cycle cost. In a European study of the life of repairs (mainly patch repair), it was found that repairs had a short life in practice [2]. A completely different situation exists for cathodic protection (CP) as a repair method. Cathodic protection of reinforcing steel has been applied to concrete structures with corrosion damage in Europe for about 25 years and slightly longer in the US [3–7]. A recent study reports on long term performance of CP systems in UK motorway structures [8].

Based on TNO's role as designer of CP systems for concrete structures, a research project was initiated, called CP + Performance Toolbox. CP companies, concrete repair companies and consultants were participants in the project. It includes improved numerical modelling for design of CP systems and analysis of their service life, resulting in prototype tools for design and life cycle costing.

This paper presents results from a survey of CP systems in The Netherlands. Until 2010, about 150 structures have been provided with CP since 1987. Sufficient documentation of design, performance and maintenance is available for working life analysis of about 105 of those systems. The large majority has provided corrosion protection for a long time. Degradation of components has occurred in some systems and failure of components as a function of age has been quantified. In a limited number of cases, intervention (repair or replacement of components) has been necessary for electrical connections, primary anodes, reference electrodes and power units. Failure of parts of the anode system has occurred with a rate that increases with age. Taking CP system life until interventions are necessary as the main criterion, the mean service life is about 15 years. However, complete failure of the anode was rare; and no cases have been reported where reinforcement corrosion had reappeared.

Consequently, maintaining good corrosion protection in previously corroding concrete structures using CP over for example 25 years is mainly a matter of maintaining the CP system. Based on analysis of the field data a life cycle cost tool was built. Results will be given for example cases.

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2. Components of CP systems

A CP system for protection of steel in concrete basically consists of a conductor called the anode from which a small direct current flows through the concrete to the reinforcement, see Fig. 1. The steel potential becomes more negative and corrosion is suppressed. The anode can be either directly applied to the concrete surface (e.g. a conductive coating) or consists of a mesh of activated titanium or carbon fibres embedded in a cementitious overlay. Other types comprise titanium strips in boreholes or slots filled with cementitious mortar. The anode material (with or without overlay) is fed by a primary anode (PA, a metal wire, mesh or strip), together they form the anode system. The anode system is linked through anode-copper connections and isolated copper cables to the power unit.

Further components are reference electrodes that are used as monitoring sensors for checking protection and a low voltage power source. In order to ensure that the CP system works properly routine monitoring is performed by electrical measurements (depolarisation) at least twice a year; visual inspection is carried out once a year [9]. In most cases, a maintenance contract is agreed between the CP company and the owner of the structure, which usually runs for 10 years and that includes routine monitoring and replacement of failing components.

The anode system is the most expensive part of a CP system: it may cost between 60% and 90% of the total cost, depending on the size of the system. Within the anode system, the anode itself (conductive coating, titanium mesh and overlay) is the most expensive part. Primary anodes are the next expensive parts; primary anode-copper connections are third.

3. Failure modes

Failure of a CP system (e.g. current stops flowing) causes loss of protection to a degree or extent that depends on the type of failing component. Various failure modes occur: power units may stop working, anode-copper connections may corrode, reference electrodes may fail and anode materials or primary anodes may degrade. The effect of failure of different components will differ: when a part of the central power system fails, current will stop flowing to the whole system, eventually ceasing protection. However, if only a part of the system fails, this will result in local unprotected areas. Failures in the total CP system will be detected during the next (routine) protection check, within half a year or less. Local failures might be unnoticed during a protection check, but these will be picked up during the yearly visual inspection. Previous work has shown principles, conceptual models for degradation, practical observations and strategies to avoid such failures [10].

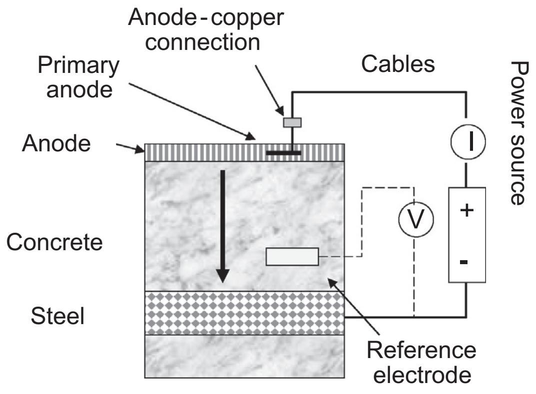

Fig. 1. Basic setup of a concrete CP system.

The most common types of failure and their effect will be explained below.

Power unit failure will occur instantly (e.g. due to lightning strike) and will cause the whole system to shut down. Primary anode or anode-copper connection failure prevents current flowing to at least part of the system. Reference electrode failure hinders protection checks. Anode degradation (due to oxidation of carbon particles or acid formation in the bond plane) increases cell resistance and may cause bond loss. This in turn will cause the need to increase the driving voltage, further accelerating degradation. After some time it becomes impossible to maintain sufficient current for full protection [11]. Global anode failure means the need for complete replacement of the anode, involving high costs. Medium levels of costs are involved for primary anode failure. The other types of failure can be corrected for less money, like replacing a failed power unit.

However, it should be noted that anode system failure does not cause immediate loss of protection. Some of about 700 conductive coating CP systems in a UK motorway complex have shown significant coating degradation (estimated from a photo up to 50% of the surface), but according to polarisation testing, these CP systems were still working properly, i.e. providing corrosion protection [8]. Similar cases of coating anode degradation but sufficient protection for several years have been observed in the survey reported here. Apparently, there is no simple and hard criterion for degradation related anode system failure. What looks like system failure does not bring about reactivation of corrosion in the short term. Instead, the need for "non-negligible maintenance" is used here as the criterion for the end of the working life, which is conservative.

4. Statistical analysis of field data

The statistical technique of survival analysis was used for the analysis of service life data on concrete CP systems and components. In general, survival analysis involves modelling time-to-event data. That is, the data consists of objects (e.g. patients, engines, CP systems) together with a time until a particular event occurs (e.g. death, failure). See [12] for a comprehensive survey of survival analysis. In this case the events are particular types of failure of CP systems, like global or local failure of the anode or failure of primary anodes, connections or reference electrodes. The goal of the analyses is to quantify and then predict time until failure. One of the difficulties in analysing failure time data is that for some existing objects the time to failure is not known. Reasons can be:

- the object is still working now, or
- after a last known point in time in the past at which the object was still working, there has been no further information on the object, for instance due to lack of monitoring.

This lack of information after a certain point in time is called (right-) censoring. Now, for every object in the group under analysis we can specify a time after which the object has either failed or been censored. There are various techniques that take this censoring into account. One of the results one would like to obtain from the analysis is the survival function $S(t)$, a function in time describing the probability to survive up to and including time t, or its complement, the failure function $F(t) = 1 - S(t)$, indicating the probability to have failed at or before time t. In order to estimate the survival function, one can use non-parametric or parametric methods.

The Kaplan–Meier estimator (see [12, Section 1.4]) is called non-parametric because it does not assume a particular distribution type of the survival function (like normal, exponential, etc.).