



Throwing power of cathodic prevention applied by means of sacrificial anodes to partially submerged marine reinforced concrete piles: Results of numerical simulations

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ABSTRACT

The paper deals with the determination of current and potential distribution in reinforced concrete elements partially submerged in seawater aimed at predicting the throwing power of cathodic prevention applied by means of sacrificial anodes. Experimental results from previous laboratory tests showed that the throwing power of cathodic prevention is higher compared to that of cathodic protection [1]. In order to extend the results obtained on small-scale specimens to elements of higher dimensions, FEM numerical simulations of potential distribution were carried out. Several cases were considered, representative of conditions differing in electrochemical behaviour of steel bars, geometry of the pile and of sacrificial anodes, concrete resistivity. The results allowed to discuss the role of different factors on the throwing power that can be reached by using sacrificial anodes immersed in the seawater to protect reinforcing steel bars in the emerged part of a pile.

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1. Introduction

Chloride induced corrosion is one of the main deterioration phenomena affecting the durability of reinforced concrete structures exposed to seawater. Chlorides penetrate the concrete cover and cause the onset of pitting corrosion when their concentration at the steel surface exceeds a critical threshold value. This threshold depends on several factors, such as pH of concrete, steel potential and presence of microvoids in the cement paste [2,3].

Cathodic prevention is an electrochemical technique aimed at delaying the onset of corrosion in reinforced concrete structures subject to chloride penetration [2,4–6]. It is applied in the same way as cathodic protection, i.e. applying a cathodic current to the reinforcement through an external anode, but, unlike cathodic protection, it is applied when chlorides have not reached the critical threshold at the reinforcement and the steel is still passive. Cathodic prevention relies on the increase in the critical chloride threshold for the initiation of corrosion due to a cathodic polarisation of the steel. As a consequence, the time necessary for chlorides to penetrate the concrete cover and reach the critical content at the steel surface is increased and the service life of the structure is extended [5]. Cathodic prevention operates at much lower current densities (about 1–2 mA/m² of steel surface) compared to cathodic protection (10–20 mA/m²). Owing to its higher throwing power and thus the lower

risk of overprotection, it can be safely applied to prestressed structures without any risk of hydrogen embrittlement [6].

Marine structures which are partially submerged in seawater show some peculiarities. Here the higher risk of corrosion usually occurs in the emerged part of the structure (in particular the tidal and splash zones), where both oxygen and chlorides are available. Conversely, the steel bars in the permanently immersed concrete are usually free from corrosion, owing to the lack of oxygen and consequent very negative potential values (typical of saturated conditions) that promote high chloride threshold values for corrosion initiation.

The possibility of protecting steel bars in the emerged part of these structures through the use of sacrificial anodes (either immersed in seawater or embedded in the structure) has been investigated by several authors [1,7–10]. In particular, the possibility of protecting the reinforcement by means of sacrificial anodes which are simply submerged and electrically connected to steel bars would be very attractive since it would allow to reduce the costs related to the application. However, a possible limitation is the “throwing power” of the protection, i.e. the height at which protection can be achieved: it appears that this height is limited to a few tens of centimetres above the water level, depending on the concrete resistivity [7,8]. The use of cathodic prevention, instead, can avoid this limitation owing to the higher polarisability of passive steel compared to that of active steel [1,11].

Indeed, previous experimental tests carried out on reinforced concrete columns 0.15 × 0.15 × 1.20 m showed that, if sacrificial anodes were applied when the concrete was free of chloride and

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steel bars were still passive, even the highest bar, placed at 1 m from the level of water, was under polarisation conditions that prevented corrosion initiation (as indicated by 4-h potential decay values higher than 100 mV [6]). Conversely, if steel bars were already corroding, polarisation conditions sufficient for protection (4-h decay >100 mV) could be reached only up to about 0.6–0.8 m from the water level. This result is shown in Fig. 1, that plots the 4-h decay of bars placed at different heights in the two cases of cathodic protection and prevention.

In order to extend these results to more realistic elements of higher dimension and different geometry, numerical simulations of current and potential distribution were carried out on models representative of reinforced concrete piles containing steel bars at different heights, protected with sacrificial anodes placed in the water and connected to steel bars. Boundary conditions describing the electrochemical behaviour of bars and values of concrete resistivity were obtained from the results of previously mentioned experimental tests.

This paper presents the results of the numerical simulations: first the numerical model was calibrated with the results obtained from experimental tests presented in [1]; then the models were used to study the effect of different parameters on the throwing power of the techniques. Compared to existing literature on simulation of current distribution in partially submerged concrete structures, this work aimed at making a systematic comparison between the cases of protection and prevention. Several cases were considered, representative of conditions differing in geometry and dimension of elements, position and dimension of sacrificial anodes, position of the water level, use of a blended cement that increases concrete resistivity, with the aim of highlighting and quantifying the possible benefits that can be achieved with cathodic prevention.

2. General description of the models

The numerical models were aimed at determining the distribution of potential and current in a system describing a concrete element containing steel reinforcement partially immersed in seawater and protected with submerged sacrificial anodes. In general, this problem requires to solve Laplace's Eq. (1) together with Ohm's law (2):

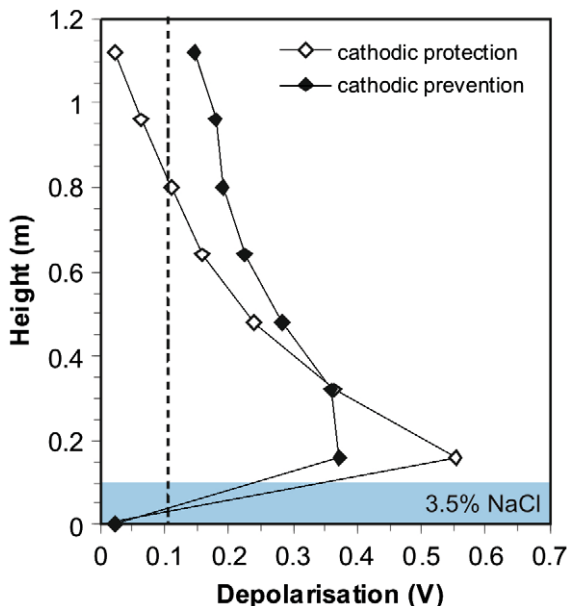


Fig. 1. Comparison of experimental data of 4-h decay along the height of the columns subjected to cathodic protection and cathodic prevention [1].

$$\nabla \cdot (-\kappa \nabla V) = 0 \quad (1)$$

and

$$i = -\kappa \nabla V \quad (2)$$

where κ indicates the conductivity ($\Omega^{-1} \text{m}^{-1}$), V is the potential (V) and i the current density (mA/m^2) [12]. In the present work a finite element method was used to make calculations of potential distribution with a commercial software [13].

Owing to the higher electrical conductivity of metals compared to that of concrete or seawater, the rebars and the anodes were assumed to be equipotential regions, and were not considered in the domain where Laplace's equation was solved; their electrochemical behaviour was introduced through proper boundary conditions at the boundary representing the interface with the electrolyte.

Different boundary conditions were introduced. Polarisation curves describing the kinetics of electrochemical reactions were imposed at the steel/concrete interface, either in the form of Butler-Volmer equations:

$$i = i_0 \cdot \{ \exp(2.303 \cdot (V - V_0)/b_a) - \exp(-2.303 \cdot (V - V_0)/b_c) \} \quad (3)$$

or by introducing the limiting current of oxygen diffusion:

$$i = \frac{1 - \exp(-2.303 \cdot (V - V_0)/b_c)}{\frac{1}{i_0} + \frac{\exp(-2.303 \cdot (V - V_0)/b_c)}{i_{\text{lim}}}} \quad (4)$$

In the previous equations, i_0 is the corrosion current density (mA/m^2), V_0 the free corrosion potential (V), i_{lim} the limiting current density of oxygen (mA/m^2), b_a and b_c the anodic and cathodic slopes of the polarisation curves (mV/dec).

For rebars embedded in the submerged concrete, simple conditions of constant current density were applied, taking into account the limiting conditions due to lack of oxygen under both free corrosion and cathodic polarisation:

$$i = i_{\text{const}} \quad (5)$$

On the surface of the anodes, a condition of constant potential was imposed (i.e. the anode was assumed to be non-polarisable):

$$V = V_{\text{an}} \quad (6)$$

All the other boundaries, such as border of the geometry or rebars not connected to the anode, were characterised by insulation conditions:

$$i = 0 \quad (7)$$

The resistivity of the concrete was selected taking into account differences in the water content and chloride content in the concrete along the height of the column, as it will be explained later. The resistivity of seawater was assumed equal to $0.2 \Omega \text{m}$ in all cases.

3. Calibration of the model with experimental data

A first series of simulations was carried out to calibrate the model and to check its capability to describe the considered phenomena. The same geometry of the laboratory specimens was considered and parameters measured on the specimens, such as V_0 , i_0 , ρ , were introduced in the model. The specimens consisted of concrete columns $0.15 \times 0.15 \times 1.20 \text{m}$ containing 15 horizontal steel bars at different heights and placed in a 3.5% NaCl solution, in a way that only the lower rebar was permanently immersed. The rebars were electrically connected to each other and with Al-Zn-In alloy discs (anodes) immersed in the solution. This simple geometry allowed the measurement of the protection current picked-up by each single bar. In one case the concrete was initially chloride-free and steel bars were passive, thus representing conditions of application of cathodic prevention; in the other case, chlorides

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