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Rebar Corrosion Rate Measurements for Service Life Estimates

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ABSTRACT:

Reinforcement corrosion is the main cause of damage and early failure of reinforced concrete structures worldwide with subsequent enormous costs for maintenance, restoration and replacement. Traditional methods used today for assessment of reinforcement corrosion are based on electrochemical techniques that determine the free corrosion potential or polarization resistance.

However, these methods suffer from problems both with interpretation of results, (e.g. potential measurements in wet and water saturated concrete) and time required for each test (e.g. determination of corrosion rate by linear polarization technique takes approx. 4 minutes per measurement).

In an attempt to overcome these problems, a rapid non-destructive polarization technique has been developed for application to reinforced concrete structures. This technique, called the galvanostatic pulse method, is based on the polarization of reinforcement by means of a small constant current. The applied current results in an exponential anodic change of the reinforcement potential. The corrosion rate can be deduced from the nature of this potential change if the corroding area of the reinforcement below the concrete surface is known.

Equipment has been developed based on this principle, which enables corrosion rate measurements to be made in less than 10 seconds. The half-cell potential and the electrical resistance of concrete are measured simultaneously. All data is easily transferred to a PC from where it can be plotted and evaluated further.

This paper presents the results and analysis of measurements performed on the pillar of a highway-bridge exposed to de-icing salts. If these measurements are repeated at regular time intervals and corrected for variations in temperature and humidity, the results may be used for service life prediction of the structure.

Modern reliability based methods of evaluating the residual service life of deteriorating structures need factual data of the key parameters of ongoing deterioration mechanisms. The value of such an approach is that the uncertainty associated with the data of the different input parameters can be included in the probabilistic calculation. This enable a factual calculation of the level of reliability associated with the service life prediction, changing "educated guesswork" to factual information on uncertainties associated with the predictions.

1. Introduction

Reinforcement corrosion is the main cause of damage and early failure of reinforced concrete structures worldwide with subsequent enormous costs for maintenance, restoration and replacement [1]. For example the European infrastructure has reached an age where the capital costs have decreased but the maintenance costs have grown to such an extent (5 billions EURO per year) that they constitute a major part of the current costs of the infrastructure [2].

One estimate from the United States [3] is that the cost of damage to reinforced concrete bridges and car parks due to de-icing salts alone is between 325 to 1000 million of EURO per year. In the UK, the Department of Transport estimates a total repair cost of 1 billion EURO due to corrosion damage on motorway bridges [4]. These bridges represent about 10% of the total inventory in the UK.

Maintenance and planning of the restoration of these structures as well as quality control requires reliable and non-destructive techniques that can detect corrosion of rebars at an early stage which can accurately delineate parts of the structure in need of repair and which can determine the corrosion rate.

Decisions on whether to repair or to demolish structures may depend on the estimated remaining service life. In the last few years much attention has been given to developing methods for predicting remaining service life of the structure. Most of the reported work deals with corrosion of concrete reinforcement [5],[6], and 7]. These methods primarily involve the use of mathematical models and lifetime extrapolation based on corrosion current measurements. Predicting remaining service life usually involves making some type of time extrapolation from the present state of the concrete to the end-of-life of the state [8].

This paper presents results of galvanostatic pulse technique, a rapid electrochemical polarization method, which allows reliable evaluation of reinforcement corrosion and estimation of corrosion current (and also corrosion rate if the area of polarized reinforcement is known) in less than 10 seconds [9]. The galvanostatic pulse equipment has been developed with easy data export to PC systems for plotting of the measured free corrosion potential, electrical resistance of concrete and corrosion rate of reinforcement.

This technique has been used for measurements of corrosion rate on a pillar of a highway-bridge in Denmark exposed to de-icing salts. These measurements have been performed since 1994 and later, from 1998, supplemented with monitoring of corrosion current by means of the post mounted sensors embedded in concrete [10]. The results of these measurements and their utilization in the service life models are presented in this paper.

2. Galvanostatic Pulse Technique for Assessment of Reinforcement Corrosion

2.1. General Description

The galvanostatic pulse method is a transient polarization technique working in the time domain. The method set-up is shown in Fig. 1.

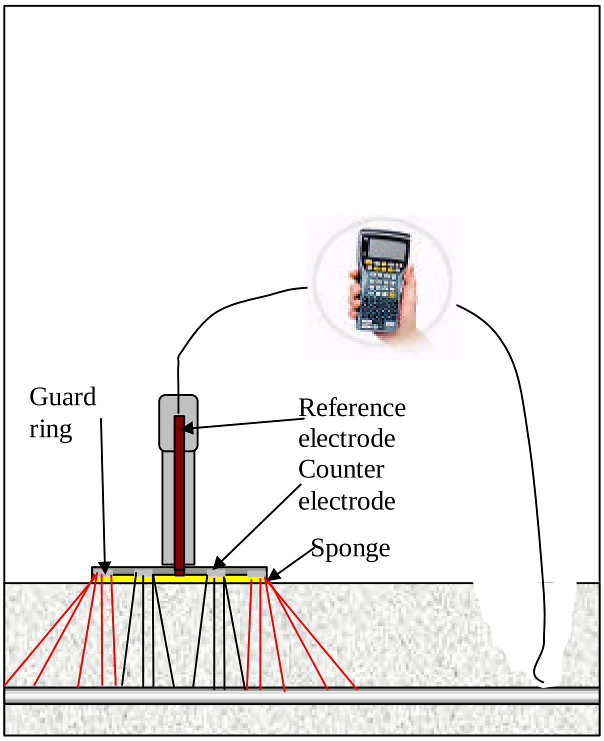

Fig.1: Set-up of the galvanostatic pulse technique

A short time anodic current pulse is imposed galvanostatically on the reinforcement from a counter electrode placed on the concrete surface. The applied current is usually in the range of 5 to 400 ? A and the typical pulse duration is up to 10 seconds ?9?,?11?. The reinforcement is polarized in the anodic direction compared to its free corrosion potential. A reference electrode (in the center of the counter electrode) records the resulting change of the electrochemical potential of the reinforcement as a function of polarization time. A typical potential transient response is shown in Fig. 2.

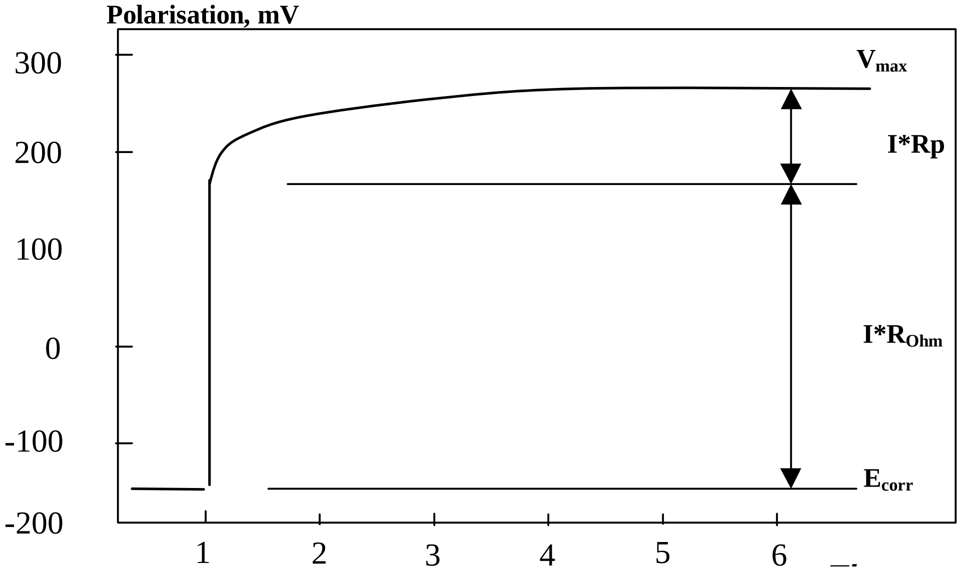

Fig.2: Typical potential time curve as response to a galvanostatic pulse

When the constant current I_{app} is applied to the system, an immediate ohmic potential jump and a slight polarization of the rebars occur (Figure 2). Under the assumption that a simple Randles circuit describes the transient behavior of the rebars, the potential of the reinforcement, $V_t(t)$, at a given time t can be expressed as ?12?:

$$(1) \qquad V_t\,(t) = I_{app}\,[Rp[\,1\text{-}\exp(-t\,/\,Rp\,Cdl)] + R_{?}\,]$$

where:

Rp = polarization resistance
Cdl = double layer capacitance
$R_?$ = ohmic resistance

In order to obtain the values of Rp and C_{dl} and the ohmic resistance $R_?$ (1) has to be evaluated further based on the experimental values. Two different methods, a linearization ?9? and an exponential curve fitting procedure ?13? can be used for calculations. In this paper only the linearization method has been applied.

Linearization

Equation 1 can be transformed in a linear form

$$(2\,) \qquad \ln\,(V_{max} - V_t\,(t)) = \ln\,(I_{app}\,Rp) - t/(RpC_{dl})$$

where V_{max} is the final (and experimentally unknown) steady potential value reached after long polarization. Extrapolation of this straight line to t = 0, using least square linear regression analysis, yields an intercept corresponding to $\ln(I_{app}{*}Rp)$ with a slope of $1/(Rp{*}C_{dl})$. The remaining overpotential corresponds to $I_{app}{*}R_?$ which is the ohmic voltage drop.

1.1. Experimental work

1.1.1. Test site

The tests were performed on a highway bridge in the outskirts of Copenhagen. This bridge was constructed in 1970 and consists of three bridge pillars with dimensions 3x0.6x5 meters. The pillars are exposed to de-icing salts approximately three months every year. Figure 3 shows the picture of the pillar where measurements have been performed since 1994.

Fig. 3: Measurement site

2.2.2. Procedure of measurements

The first measurements reported in this paper were performed in 1994 using the galvanostatic pulse equipment. As described in section 2.1 the galvanostatic pulse method enables calculation of the polarization resistance of reinforcement. The calculated polarization resistance cannot be converted to a corrosion rate unless a second concentric electrode, a “guard ring” is introduced to confine the current to an area equivalent to the central counter electrode (see fig.1). When the diameter of the reinforcement and its exposed length is known, the confined area can be calculated.

Faraday’s law of electrochemical equivalent states that 1 ?A/cm^2 corresponds to a cross section loss of carbon steel of approximately 11,6 ?m/year. The corrosion rate can therefore be estimated as.

Corrosion Rate = 11,6 x I_{corr}/A

where the corrosion rate is given in ?m/year, I_{corr} is the corrosion current in ?A calculated from polarization resistance by means of Stern Geary equation ?14?:
$I_{corr} = 25/R_p$ and A is the confined area in cm^2 of the reinforcement.

Since 1998 the galvanostatic pulse readings have been followed up by measurements using post mounted sensors embedded in the pillar at 8 different locations. A sensor of this type consists of two electrodes, one that is of the same metal as reinforcement (carbon steel) and which will corrode at high chloride concentrations in concrete and the second of a noble metal such as titanium ?10?.

By measuring the electrical current between these two electrodes it is possible to determine the time to corrosion initiation. Another option is to measure current between carbon steel electrode of the sensor and the reinforcement, which is still passive. This option has been used during the measurements on the bridge pillar.

The current is very low when both electrodes are passive and increases rapidly when the carbon steel electrode starts to corrode.

If the electrodes are installed in pairs in the different but defined depths in the cover it is possible to estimate when the corrosion on the reinforcement can be expected.

The positions of the post mounted sensors and the galvanostatic pulse measurements points are shown in fig.4.

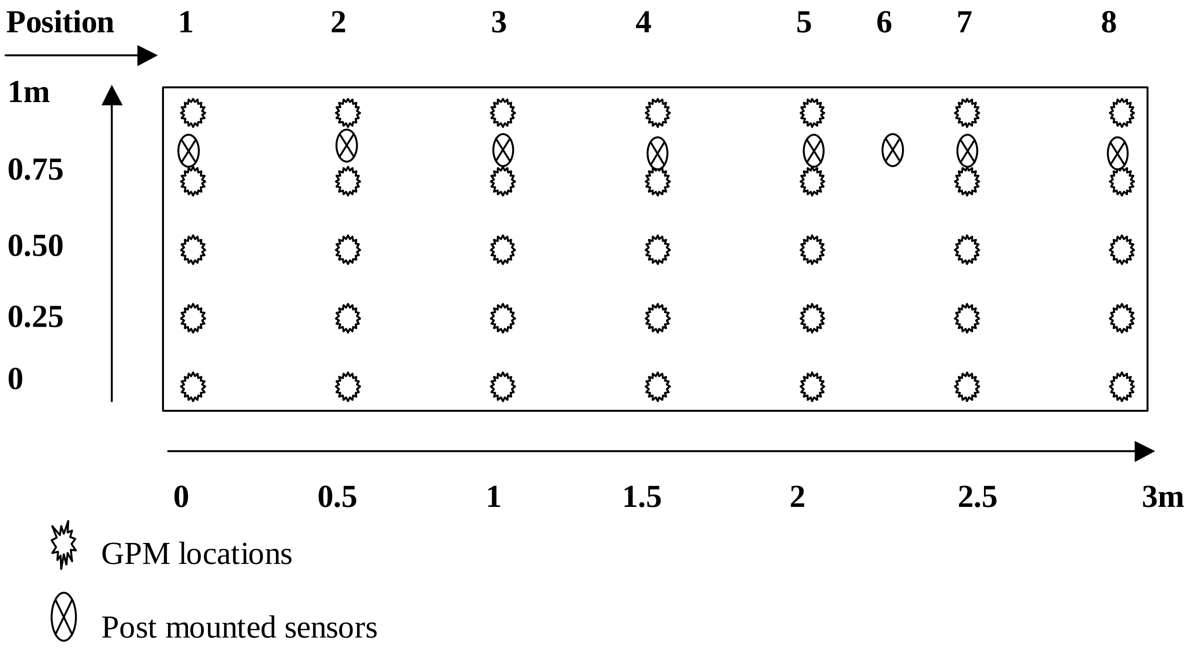

Fig.4: Location of galvanostatic pulse measurements and post mounted sensors on the pillar of the highway bridge.

2.2.3. Results

As mentioned above the galvanostatic pulse measurements have been performed since 1994. Some results of these measurements are shown on fig.5.

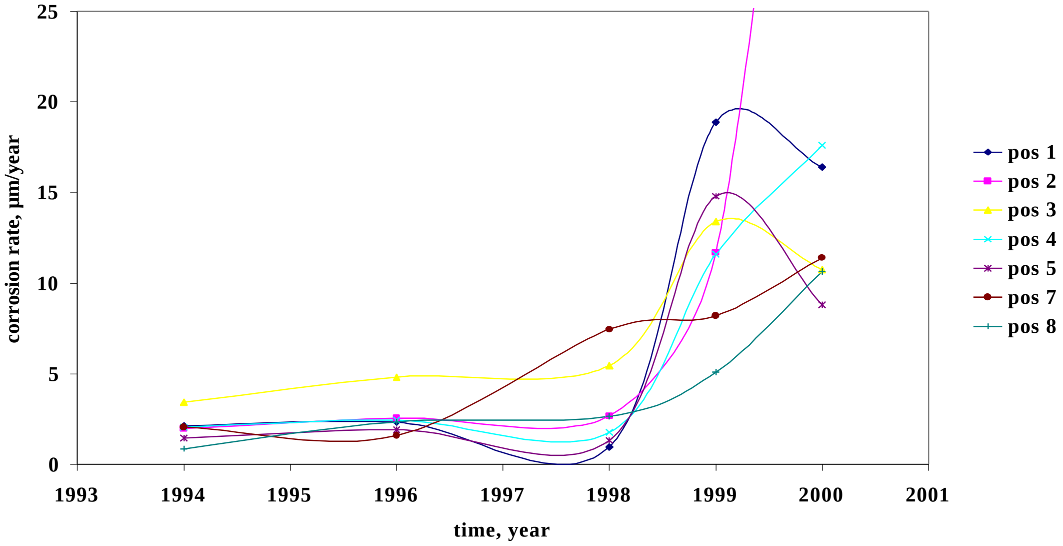

Fig.5: Corrosion rate measured in 7 locations on the pillar at 75 cm height.

The measured corrosion rates vary with time but were very low in the first four years. Since 1998 increasing values were registered in all 7 locations, which indicates the break down of passivity and initiation of active corrosion on the reinforcement.

Since 1998 the determination of corrosion rate by means of the galvanostatic pulse were supplemented by measurement of corrosion current using post mounted sensors. The variations of the corrosion current with time are shown in fig.6.

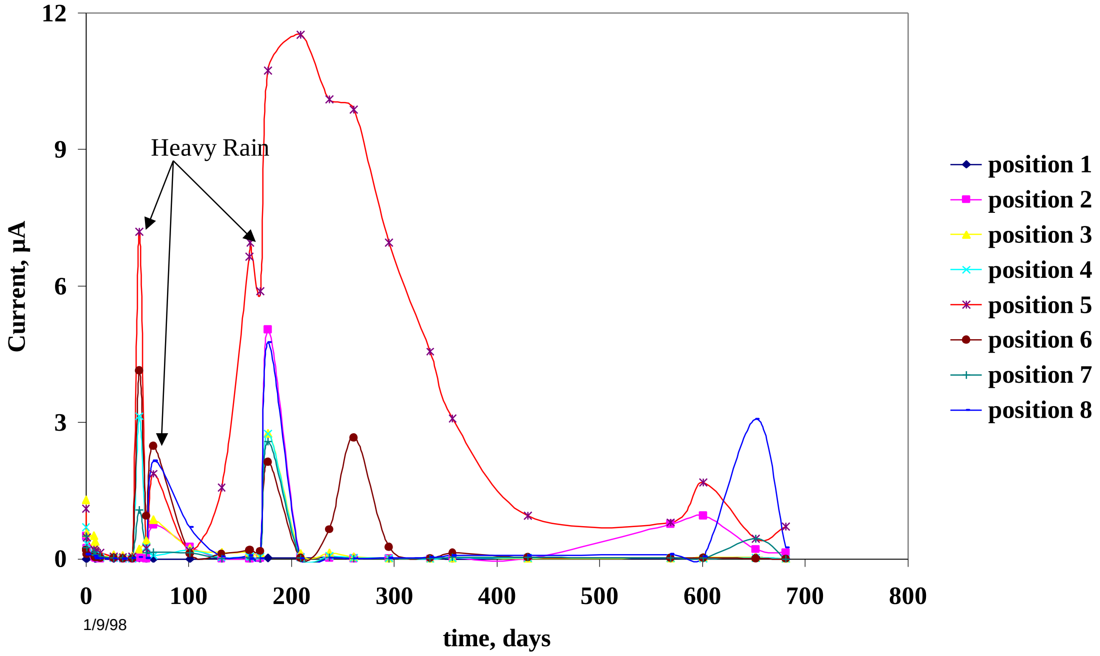

Fig.6: Variation of corrosion current with time

The post-mounted sensors are mounted in the same depth as the reinforcement (approx. 30 to 40 mm from the concrete surface). The interval between measurements is about 30 days. It is obvious that the measured current is greatly influenced by the concrete resistivity. The concrete resistivity is dependent on the humidity and temperature. Therefore the periods with heavy rain result in high increase of the measured current due to low resistivity of concrete while lower values are registered when the concrete is dry.

The comparison between the corrosion rate values determined by the galvanostatic pulse equipment and the corrosion current measured by means of the post mounted sensors is shown on fig. 7.

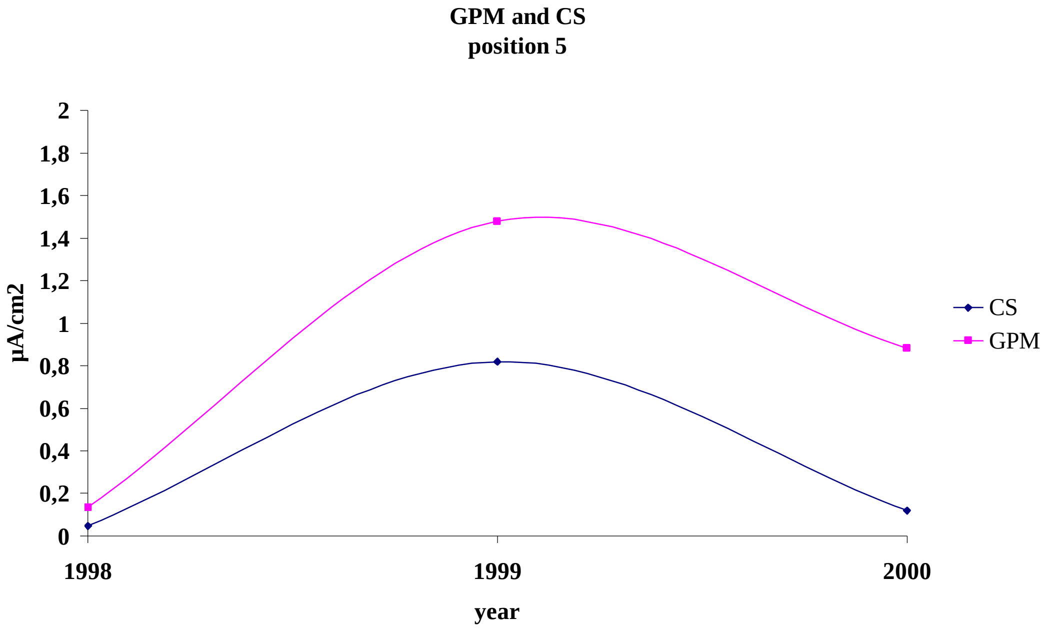

Fig. 7 Comparison of corrosion current determined by galvanostatic pulse (GPM) and measured with post mounted sensors (CS).

The measurements shown on figure 7 were performed at location No. 5 over the last three years. In this case the corrosion current determined by means of the galvanostatic pulse follows the current measured by the post-mounted sensors. The only difference is the absolute value of the measured corrosion current, which is always slightly higher in case of the galvanostatic pulse technique. The same good correlation should not always be expected because of probable local differences in the corrosion pattern. Quite large differences in corrosion activity can be expected even over small distances. These differences in corrosion activity are dependent on the local moisture conditions and oxygen availability.

The galvanostatic pulse equipment provides an option for visualization of the measured corrosion rate in a 2D (two-dimensional) plot. It is therefore identical with the option available using the traditional half-cell potential equipment ?15?. The difference is, however, that the half-cell potential provides only qualitative information with the possibility to distinguish between local passive and corroding areas.

Fig.8 and fig. 9 shows 2D plots of corrosion rate measured in 1994 (fig.8) and 2000 (fig.9).

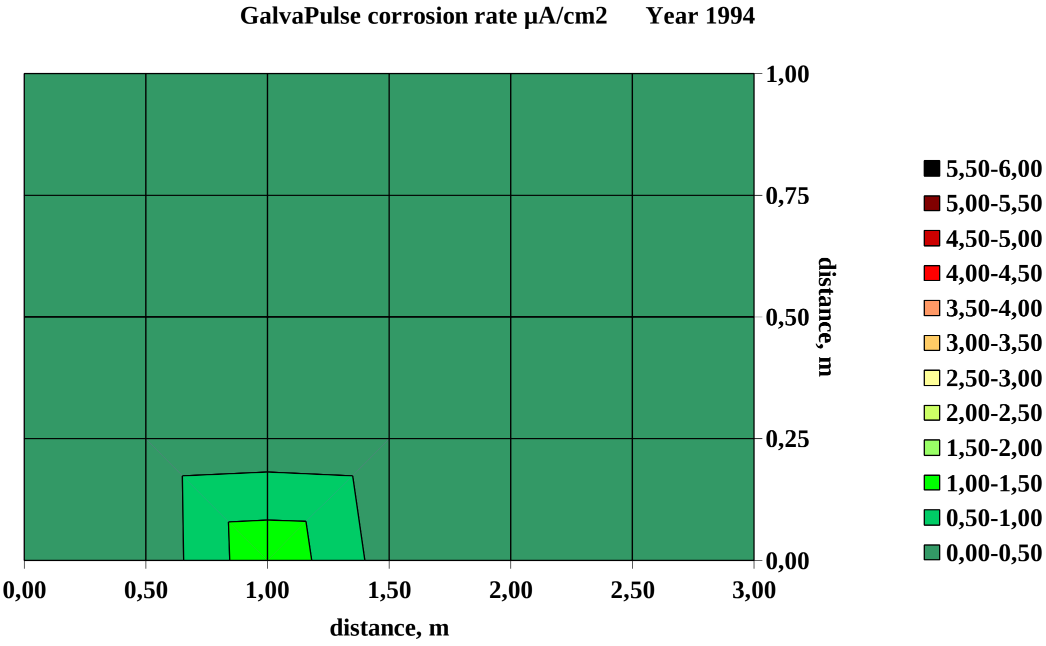

Fig. 8: 2D plot of corrosion rate values determined in 1994.

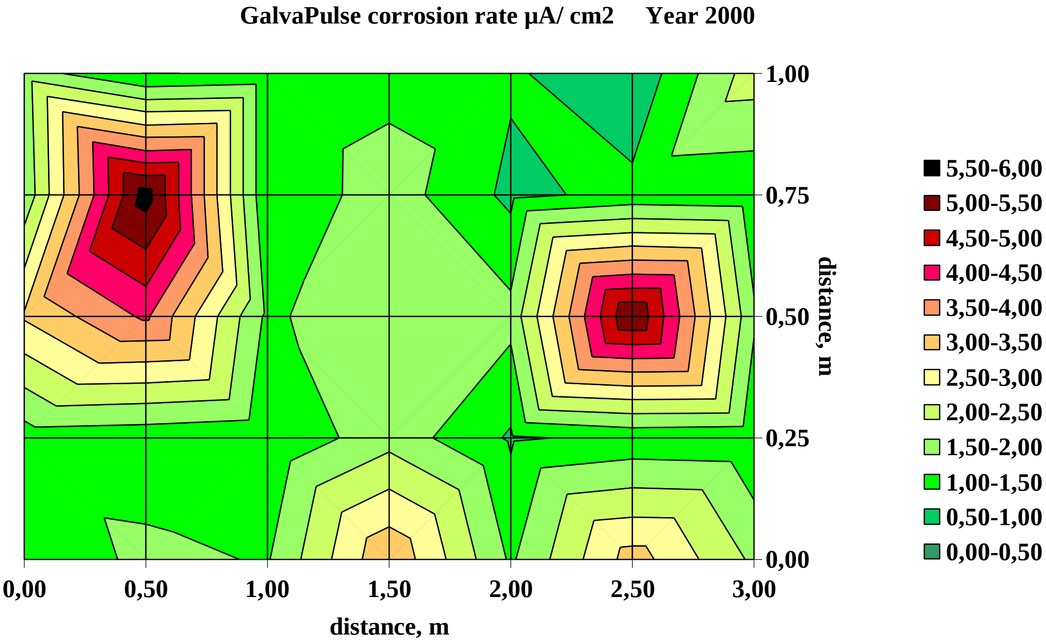

Fig. 9: 2D plot of corrosion rate values determined in 2000.

By comparison of these two plots it is obvious that in 1994 the corrosion rates in the measured area of the pillar were very low and within the passive range. Six years later it is easy to distinguish at least four locations with active corrosion (purple and brown colors on the plot of fig. 9, e.g. y=0,75 cm, x = 0,50 cm where the corrosion current is between 5.5 and 6 ?A/cm^2 corresponding to corrosion rate of about 60 ?m/year).

The corrosion rate values measured during the last six years at two levels on the pillar (50 and 75 cm) are summarized in table 1.

Table 1: Corrosion rate values measured by means of the Galvanostatic Pulse during six years at two pillars heights, 50 and 75 cm from ground level.

	Date of readings					
	12-94	06-96	08-98	08-99	06-00	07-00
Location of readings x/y (cm)	**Corrosion rate (? m/year)**	**Corrosion rate (? m/year)**	**Corrosion rate (? m/year)**	**Corrosion rate (? m/year)**	**Corrosion rate (? m/year)**	**Corrosion rate (? m/year**
50/0	**2,7**	**3,2**	**3,1**	**16,3**	**35,5**	**78,6**
50/50	**2,0**	**3,4**	**4,3**	**16,9**	**47,4**	**31,1**
50/100	**2,0**	**3,7**	**1,7**	**11,8**	**16,1**	**21,6**
50/150	**2,3**	**2,8**	**0,8**	**15,3**	**23,0**	**18,2**
50/200	**1,8**	**3,6**	**4,9**	**10,8**	**19,4**	**15,3**
50/250	**1,2**	**3,6**	**3,4**	**7,8**	**64,0**	**8,7**
50/300	**1,0**	**2,8**	**2,2**	**10,3**	**18,3**	**6,3**
75/0	**2,4**	**2,7**	**1,1**	**22,0**	**19,0**	**32,5**
75/50	**2,3**	**3,0**	**3,1**	**13,5**	**66,5**	**31,1**
75/100	**3,9**	**5,6**	**6,4**	**15,5**	**12,5**	**12,5**
75/150	**2,4**	**2,9**	**2,1**	**13,5**	**20,5**	**89,5**
75/200	**1,7**	**2,2**	**1,5**	**17,2**	**10,2**	**10,1**
75/250	**2,3**	**1,9**	**8,6**	**9,5**	**13,2**	**8,8**
75/300	**1,0**	**2,8**	**3,1**	**5,9**	**12,3**	**13,0**

During the first four years of measurements the determined corrosion rate values indicated that the reinforcement was passive and the corrosion process had not yet initiated. From 1999 the corrosion rate values increased as passivity was broken down. The propagation of the corrosion process continued after 1999 particularly in the four locations as indicated by red fonts in table 1.

At the same time it should be noted that the corrosion rate values vary with time but are also dependent on the environmental conditions during the measurements (temperature and humidity). As an illustration of this behavior the value of corrosion rate that was measured in July 2000 at the location: x/y=50/250 cm shall be noted. The increase of corrosion rate at this location culminated in June 2000 (64 ?m/year). The value had dropped to 8,7 ?m/year one month later.

For this reason a linear change of corrosion rate with time can not always be expected and this should be taken into account when attempting service life estimates.

3. Prediction of Service Life Based on Corrosion Rate Measurements

The measurements of corrosion rate have been used by both Andrade [6] and Clear [7] to estimate the remaining service life of reinforced concrete in which corrosion is the limiting degradation process. Both models used the polarization resistance technique to measure corrosion currents. The Andrade model considers reduction of the steel section as the significant consequence of corrosion instead of cracking or spalling of concrete. The corrosion current is converted to reductions in the diameter of reinforcing steel by the following relationship:

$$d(t) = d(0) – 0{,}023 * Icorr * t$$

where:

? d(t) = the reinforcement diameter in (mm) at time (t) in years after the beginning of propagation period
? d(0) = the initial diameter of the reinforcement in (mm)
? Icorr = the corrosion rate in (? A/cm^2)
? 0,023 = the conversion factor of ? A/cm^2 into mm/year

Clear based his model on the combination of laboratory, outdoor exposure and field studies. He suggested the use of the following relationships between the corrosion rates and remaining service life:

? Icorr less than 0,5 ? A/cm^2 (6 µm/year) – no corrosion damage expected.
? Icorr between 0,5 and 2,7 ? A/cm^2 (6 and 30 µm/year) – corrosion damage possible in the range of 10 to 15 years.
? Icorr between 2,7 and 27 ? A/cm^2 (30 and 300 µm/year) – corrosion damage expected in 2 to 10 years.
? Icorr in excess of 27 ? A/cm^2 (300 µm/year)– corrosion damage expected in 2 years or less.

Both models assume the linear change of corrosion rate with time. However the measured corrosion rate are changing with time depending on the variations of the temperature and humidity. To overcome this problem Andrade calculates an average corrosion rate over a year. Another way to overcome this problem is the empirical extrapolation.

Poulsen suggests the following solution of the above-mentioned problems [16], [17]. Assuming that the corrosion rate is taken place on the whole surface or reinforcement with the identical intensity, the loss of reinforcement diameter can be expressed as follows:

$$? D = 2 * R(t) * ? t$$

Where:

? ? D = loss of diameter of reinforcement
? R(t) = corrosion rate at time t

Unfortunately a uniform corrosion rate on the whole surface area can not always be expected. Therefore it is necessary to introduce a correction factor K. When the whole surface area is uniformly corroding, as often seen in the case of carbonation, the correction factor K is close to 1. Opposite when the chloride- induced corrosion takes place and local pitting occurs, the correction factor K is larger than 1.

Within a given period of time, ? t, expressed in years, the loss of diameter can be described by means of the following formula:

$$? D = 2*10^{-3} * K * R(t) * ? t$$

Where:

? ? D = loss of diameter (mm) with time,
? K = correction factor,
? R(t) = corrosion rate at time t (µm/year)

Because the corrosion rate is a function of time the loss of diameter can be described as follows:

$$? D = 2*10^{-3} * K * ?R(t) * ? t = 2*10^{-3} * K * A$$

The integral ?R(t) is equal to the area, A, under the curve of the change of corrosion rate with time.

How this model can be utilized in practice is shown below, when the measurements of corrosion rate on the bridge pillar from the 1994 to 2000 are interpreted by means of the above-mentioned model. The measurements at the location of pillar width/height (x/y) = 75/150 cm have shown moderate corrosion rate values during the first four years, from 1994 to 1998. From 1999 the measured values increased rapidly and were in the range of high corrosion rates.

In order to estimate the loss of reinforcement diameter it is necessary to calculate the area under the curve of corrosion rate of time. This curve is shown on figure 5 (location 2). The area under the curve representing location 75/150 cm is calculated to 50 µm. Assuming that the correction factor K = 3, the loss of reinforcement diameter due to corrosion will be as follows:

$? D = 2*10^{-3} * K * A = 2*10^{-3} * 3 * 50 = 0,3$ mm.

The above-mentioned calculation is only an example how the model of Poulsen can be used based on empirical data, however, the obtained value of 0,3 mm of diameter loss has not been verified by visual inspection at this location on site.

4. CONCLUSIONS:

1. The galvanostatic pulse technique is a rapid electrochemical polarization method, which enables corrosion rate measurements to be made in less than 10 seconds. The half-cell potential and the electrical resistance of concrete are measured simultaneously. All data are easily transferred to a PC from where it can be plotted and evaluated further.
2. The corrosion rate values are very dependent on the environmental conditions during measurements and the local are of the corroding rebar. Varying temperature and humidity have a great influence on the measured corrosion rate values.
3. The service life models based on corrosion rate measurements provided by Andrade and Clear assume the linear change of corrosion rate with time. Due to the influence of the environmental conditions the linearity of the change of corrosion rate with time can not be expected.
4. Poulsen developed a model, which takes the above-mentioned problem into account. The calculation by means of this model and based on the data from site performed under 6 years period has shown promising results.

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