Stochastic evaluation of active corroding areas in concrete structures

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Abstract: For a realistic and accurate description of the corrosion progress, spatial variability of corrosion processes must be accounted for, in particular for the evaluation of existing structures. To this end, structures are subdivided into zones of comparable material and environmental conditions. Each of these zones is further subdivided into elements, which exhibit correlated corrosion behaviour. In order to assess the size of the elements in the zones as well as their dependence structure, a study of the so-called correlation length or radius must be carried out for the model parameters. A problem in estimating the correlation distance is the lack of data. The aim of this paper is the analysis of the spatial variability of corrosion processes by potential mapping of two concrete structures. Potential mapping is a widely used inspection method for detection of ongoing corrosion in reinforced concrete structures. Geostatistical techniques are used to evaluate the stochastic properties like mean value, standard deviation and spatial correlation structure. It is expected that through an improved model of spatial variability, the condition of the structure and correspondingly the service life time can be predicted more accurately.

1 Introduction

Corrosion, especially in case of macrocell formation, is a major problem for reinforced concrete structures, because it can cause local loss of the reinforcement cross section in conjunction with subsequent cracking and spalling of concrete cover. With increasing deterioration the serviceability is impaired and/or the load bearing capacity decreases. The inspection and maintenance strategies to detect such damages can be costly and economical planning is mandatory.

Once corrosion gets started due to chloride ingress, anodic areas can be detected through potential mapping. Potential mapping provides two-dimensional information about a structure. This kind of information can be used for a spatial evaluation of corroding areas. It has to be considered that potential fields are influenced by several parameters such as concrete cover and/or resistivity, which always will have an effect on the spatial variability. In geostatistics the evaluation of spatial variability is commonly used to describe soil properties. The present paper focuses on an approach to analyse the spatial variability of corrosion processes by potential mapping using geostatistical techniques. Based on these results, decisions about further repair actions can be made and evaluated from an economical point of view.

2 Detection of active corroding areas

2.1 Measurement of potential mapping

Potential mapping is a widely used inspection method for detection of ongoing macro cell corrosion in reinforced concrete structures. Potential mapping is always reflecting the corrosion state at the point in time of the measurement. The results cannot give information about the corrosion state before or after the measurement. Macro cell corrosion is characterized by local distributed anodes with a low potential value which are surrounded by cathodic areas with nobler potential. These potential differences of macro-cell corrosion elements are obtained by applying a reference electrode on the concrete surface (Fig. 1). The reference electrode is connected electrically to the reinforcement.

The reference electrode will be displaced like a grid and so the potentials of a whole surface can be gathered. The guideline B3 [2] of potential mapping recommends a standard grid size of 0.25 x 0.25 m and at most a grid size of 0.5 x 0.5 m. In the technical bulletin of SIA [1] grid sizes are between 0.15 x 0.15 m and 0.25 x 0.25 m for field measurements. RILEM [13] states grid sizes of 0.15 x 0.15 m.

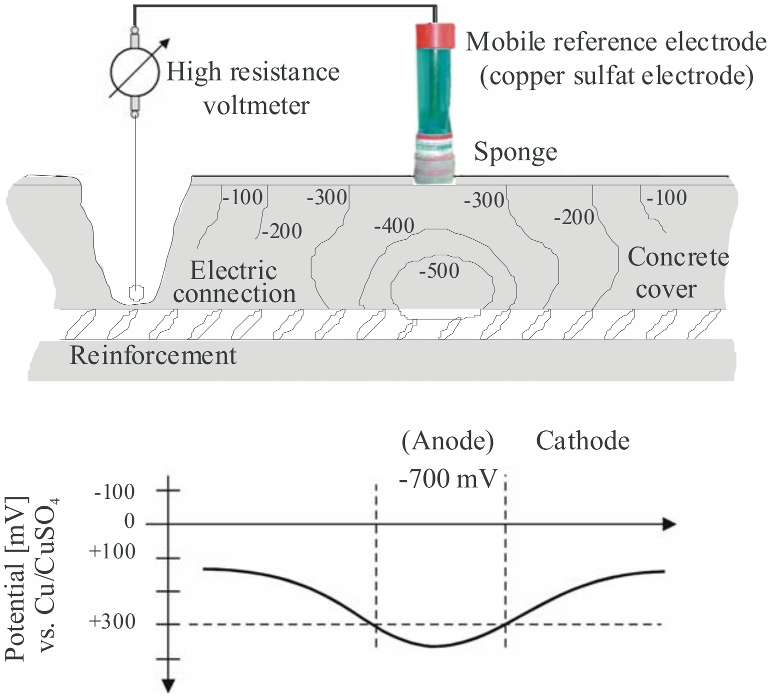

Fig. 1: Principle of potential field measurement

Potential mapping is a qualitative test method. After the evaluation of the test results there are only statements like the reinforcement is corroding or not. It is impossible to indicate the condition state of the reinforcement only with the absolute value of the potential. The aim of the evaluation of potentials is to distinguish between active and passive areas. The potentials can be divided into two probability distributions, one for active and one for passive reinforcement, with the help of frequency plots (Fig. 2). For this approach the knowledge about the real condition of the reinforcement is needed by a partial abrasion of the concrete layer. Chloride profiles or visual survey verify the results from the frequency distribution. Then a threshold potential has to be defined. The potential values that a more negative than the threshold are assumed to belong to the corroding area.

The higher potential values are part of the passive distribution. The number of corrosion indications where no corrosion takes place arises with a high limit. A lot of corroding areas will be missed, if a low threshold is chosen. The problem is to find the optimal threshold. Both conclusions can have severe consequences: either a repair is executed although it is not necessary or a wrong all-clear may bring further damages and additional costs in future.

The way in which the potential field results are analyzed today [1, 2, 13] characterizes the deterioration behaviour at a particular point in space and are not intended to reflect systematic and random differences of loads, resistances or workmanship over the structure. Various factors contribute to a spatially variable behaviour of the corrosion process.

The spatial variability of corrosion processes is influenced by the differences of chloride impact on the load side and differences of the chloride migration coefficient, concrete cover and resistivity on the resistance side. The expansion of the potential field due to corrosion is affected by the concrete cover, the resistivity, geometry and the oxygen availability at the reinforcement. These are several reasons for spatial variability of the potential field. For a more realistic and accurate description of the corrosion process, spatial variability has to be taken into account. Spatial variability of physical properties includes systematic spatial variation (variation of the mean value and standard deviation) and random spatial variation. Consider e.g. a concrete bridge deck: the chloride content at the two side-areas of the deck is normally higher than in the middle part of the deck due to the spray of chloride by passing vehicles. This implies that the probability of corrosion is higher at two side areas than in the middle. This effect is termed “systematic spatial variation”. At the same time, the chloride content varies from point to point around its corresponding mean value, independent of the area under consideration. This property is referred to “random spatial variation” [10]. The random spatial variability of the characteristic physical property can be modelled by spatial probabilistic models (random fields). The systematic spatial variation can be eliminated by the subdivision of the structure into zones. As a result of the systematic spatial variability, the probability of occurrence of a condition state in one zone cannot be expected to be the same as for another zone in the structure.

In the reliability analysis of corroding concrete structures, the correlation radius is being used to define the size of the elements into which a homogeneous zone is divided. In that way the spatial variation of any material property can be captured by modelling it as a random field discretised into elements equal in number and size as the elements of the considered zone (Fig. 3). This approach requires knowledge of the correlation radius.

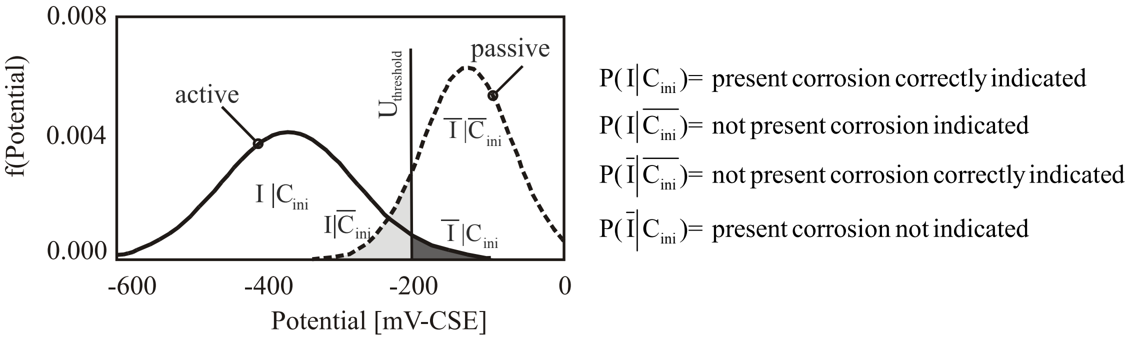

Fig. 2: Probability for indication and no indication of corrosion [9]

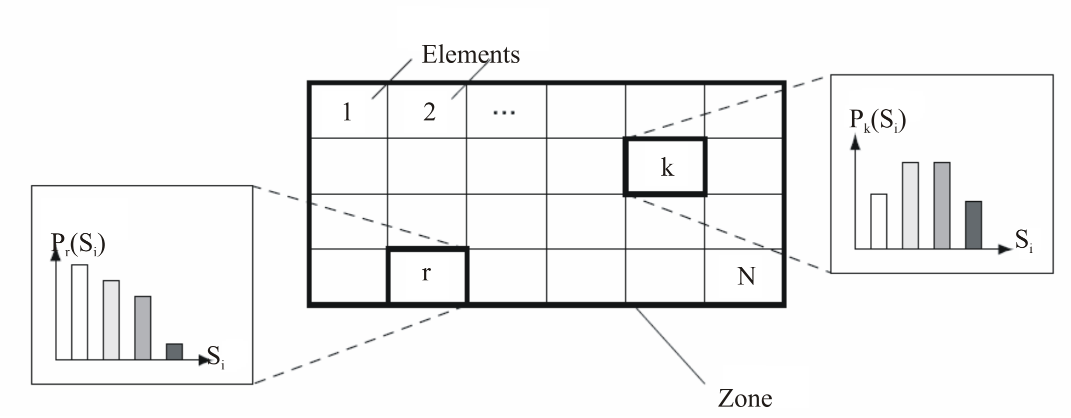

Fig. 3: Illustration of the system model. $P(S_i)$ indicates the probability of different condition states [7]

Tab. 1: Indicative values of the element size [11]

Reference	Element size [m]	Based on	Property
Li [10]	2.0	Measurements	Chloride content
Vu and Stewart [18]	0.50	Assumed	Compressive strength, cover depth, surface chloride concentration
Sterritt et al. [15]	0.50	-	Cover depth, chloride concentration
Engelund & Sørensen [6]	0.35	Measurements	Surface chloride concentration
Lentz [9]	1.00	Inspection grid size	Half cell potential measurements
Rusch [14]	1.00	Inspection grid size	Half cell potential measurements
Malioka & Faber [11]	0.40	Measurements	Air permeability
Malioka et al. [12]	0.48	Measurements	Air permeability
Straub et al. [16]	0.80	Measurements	Chloride conductivity

In order to assess the size of these elements, as well as their dependence structure, a study of the so-called correlation length or radius of the parameter governing the degradation process must be carried out. Correlation length is a measure of the range over which fluctuations in one element are correlated with those in another element. Two points, which are separated by a distance larger than the correlation distance, will each have fluctuations that are more or less independent. A problem in estimating the correlation length is the lack of data. In most studies where the spatial variability of concrete material properties is accounted for, values of the correlation radius and hence of the size of the discretised elements are based on practical considerations and experience [11].

Based on the correlation radius, the zone can be discretised to a number of individual elements. The within-elements variability of the measured material property is the same for each element and is represented by the standard deviation estimated from all the measurements.

2.2 Potential field measurement

For the practical analysis of the spatial variability of potential field measurements two different reinforced structures were chosen. The spatial variability of corrosion processes is also dependent of the use of the structure. One structure is a concrete bridge and the other an exposed parking deck.

2.2.1 Bridge

The presented structure is a bridge of a federal highway. It was measured only the two lanes in the north with bicycle lane. The measured field was 134 m long and 14 m broad. The measurement was divided into 24 segments. The potential mapping results are shown in Fig. 4. It is assumed that the bridge is a homogeneous structure, because the whole area has been exposed to a comparable chloride impact and environment and constructed with the same concrete composition.

The potential data was analysed as a bimodal distribution. So the measured data was separated into two normal distributions one representing the values which are indicating active corroding behaviour and one passive distribution. The Gaussian behaviour of the distributions was verified with statistical tests.

As a threshold potential was chosen the 95% quantile of the active distribution to be sure that a high percentage of corroding areas will be supervised. In this case the threshold potential is -160 mV (Fig. 6). The decision about the threshold potential has to be verified with additional chloride profile and partly visual inspection of the reinforcement. The threshold potential is depending on the safety level or the owner requirements and has to be determined for each structure individually.

2.2.2 Parking deck

The measured exposed parking deck has an area of about 850 m². This structure is not as homogeneous as the bridge, because the area can be subdivided into three different use cases with different chloride impact: the ramp, the cruising and the parking range. In Fig. 5, the plan of the parking deck and the potential field measurement is presented. The measured potential was not separated into the different use cases for the evaluation.

The evaluation of the potential field was the same as the evaluation of the potential field of the bridge (Fig. 7). The threshold potential of this example is $U_{threshold} = -175$ mV, which is the 95% quantile of the active distribution.

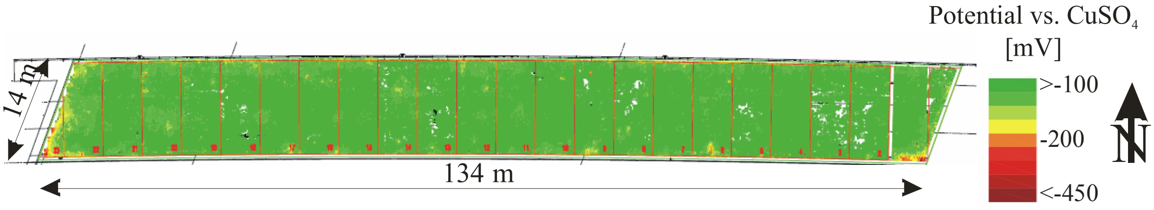

Fig. 4: Potential field measurement of the bridge

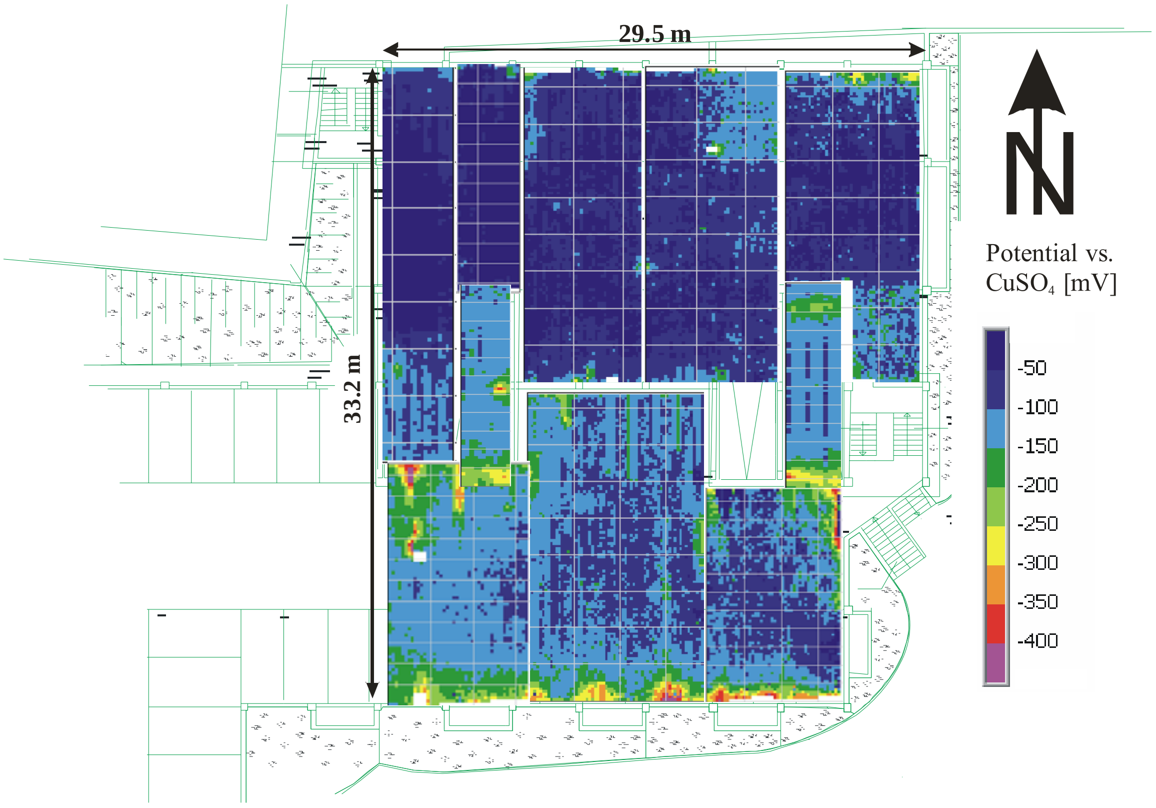

Fig. 5: Potential field measurement of the parking deck

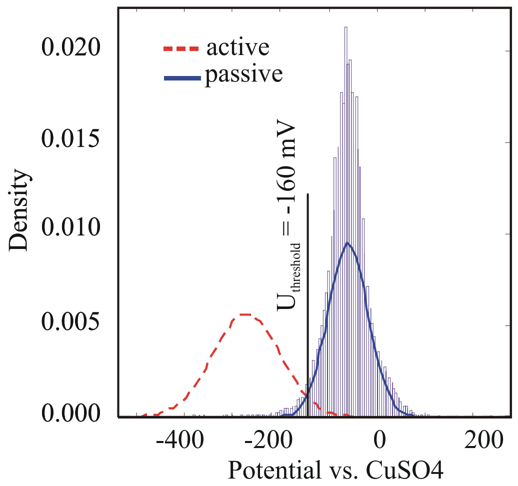

Fig. 6: Evaluation of the bridge; $U_{threshold}$ = -160 mV is the 95% quantile of the active distribution

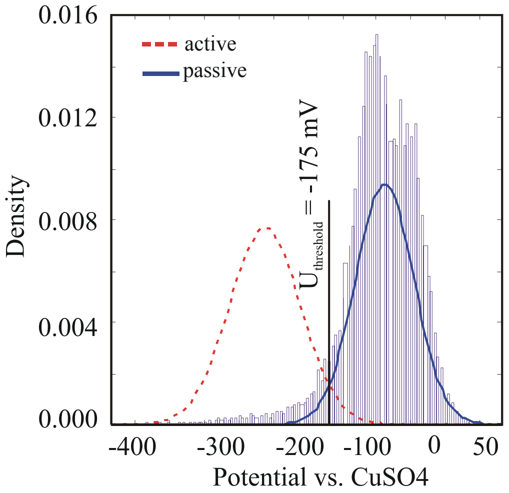

Fig. 7: Evaluation of the parking deck; $U_{threshold}$ = -175 mV is the 95% quantile of the active distribution

3 Evaluation of the stochastic properties of the active corroding areas

3.1 Theoretical background

Looking at the measurements of the potentials in both examples one can easily deduce that large areas seem to have related properties. There are more or less big zones of nearly similar values. This spatial correlation can be described by using the random field approach, taken from geostatistics as described by Chiles & Delfiner [4].

To apply the random field technique, it is assumed that the measurements of the potential are homogeneous. This implies that stochastic and spatial properties can be evaluated by analysing only a part of the measurement area. Moreover the measurement areas are assumed do be ergodic, implying that the study area is large with respect of the correlation length, as described by Deutsch [5]. In addition, it is assumed that the measurements of the potential can be described by a Gaussian random field, characterized by its mean value, standard deviation and covariance function. Analyzing the measurements no global trend could be detected.

This covariance function can be described in a variogram by the semicovariance function $\gamma(\tau)$. The so-called semivariance $\gamma(\tau)$ is defined as half the expected squared increment of the values between two locations according to Wackernagel [19]. For practitioners, Baker et al. [3] explains the variogram in equation (1). Herein X_i is the value of the random field, which is separated by the distance τ from $X_{(i+\tau)}$ and n is the number of pairs.

$$\gamma(\tau)=\frac{1}{2\cdot n(\tau)}\sum_{i}^{n}\left(X_i - X_{i+\tau}\right)^2=\rho(0)-\rho(\tau) \tag{1}$$

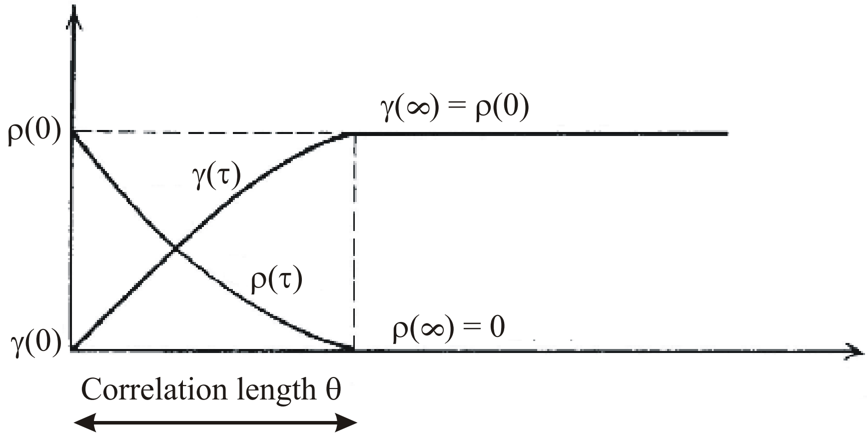

Fig. 8: Qualitative relationship between semicovariance function γ(τ) and autocorrelation function ρ(τ) of a random process according to Journel & Huijbregts [8]

In Fig. 8 the correlation length θ is introduced. Within the correlation length θ two points are correlated according to the variogram as described by Vanmarcke [17] and Journel & Huijbregts [8].

The spatial dependency of a random field can also be expressed via another more mathematical way by using autocorrelation function ρ(τ). The semicovariance and the autocorrelation function are similar for a random process with $\mu_X = 0$ and $\sigma_X^2 = 1$, as shown in Fig. 8.

Herein τ is the lag between the points. If a random field X_i has mean μ_X and variance σ_X^2 then the definition of the autocorrelation ρ(τ) is as shown in equation (2). Herein E(X) is the expected value operator.

$$\rho(\tau) = \rho(-\tau) = \frac{E[(X_i - \mu_X)\cdot(X_{i+\tau} - \mu_X)]}{\sigma_{X\,i} \cdot \sigma_{X\,i+\tau}} \tag{2}$$

In Chiles & Delfiner [4] an additional approach is presented. An exemplary random process together with an indicator i_k uses a threshold $z_k = 1.95$ is shown in Fig. 9. This indicator i_k is multiplied with the random process z_u. For this new sequence one can also apply the variogram technique.

$$i_k(u; z_k) = \begin{cases} z(u) & \text{, if } z(u) \le z_k \\ 0 & \text{, otherwise} \end{cases} \tag{3}$$

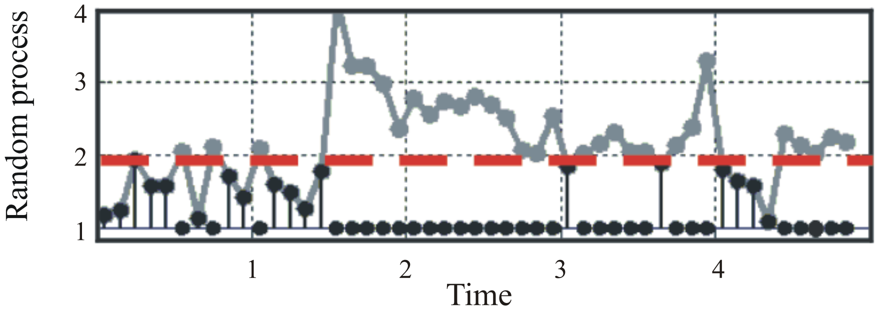

Fig. 9: Indicator approach i_k (black) applied to an exemplary random process z_u (grey)

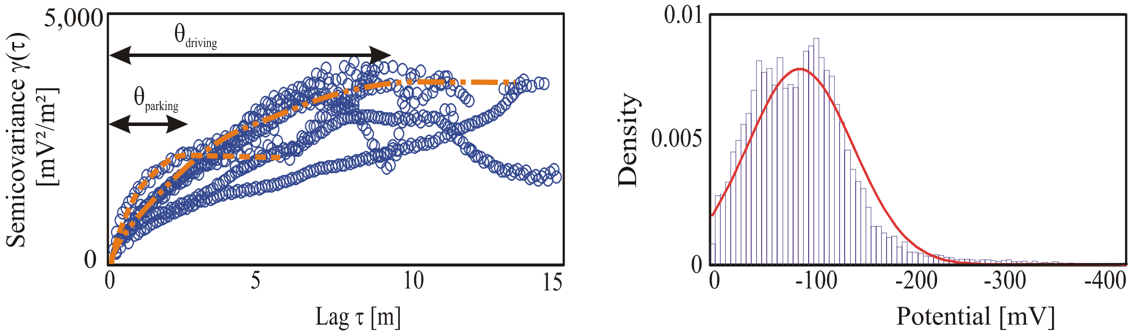

Fig. 10: Stochastic properties (left: variogram, right: histogram) of the measurements in the parking deck

3.2 Evaluation of the stochastic properties

In Fig. 10 the histogram and the variogram of the stochastic properties are shown. One can deduce the different correlation distances $\theta_{\text{parking}} = \sim 3$ m and $\theta_{\text{driving}} = \sim 10$ m. This can be deduced to the different exposition classes of the parking deck. Parking zones have a lower correlation length than the driving zones. In comparison to this, the measurements of the bridge show a comparable result for the correlation length $\theta_{\text{bridge}} = \sim 5$ m.

The variograms of the bridge shown in Fig 11 have more or less similar correlation distances in different directions (E-W, NS, NE-SW). The same was observed in the measurements of the parking deck. This indicates that the assumption of an isotropic random field is justified.

Now we have to check that the assumption of a spatial Gaussian correlation structure is correct. A spatial Gaussian correlation structure assumes that the extremes of a distribution are not correlated; just the quantils around the mean value have the biggest correlation, as described by Chiles & Delfiner [4]. The variogram cannot capture this phenomenon because it measures the spatial correlation in an integrative manner as one can deduce from equation (1) and equation (2). Extreme high or low value have no major influence on the

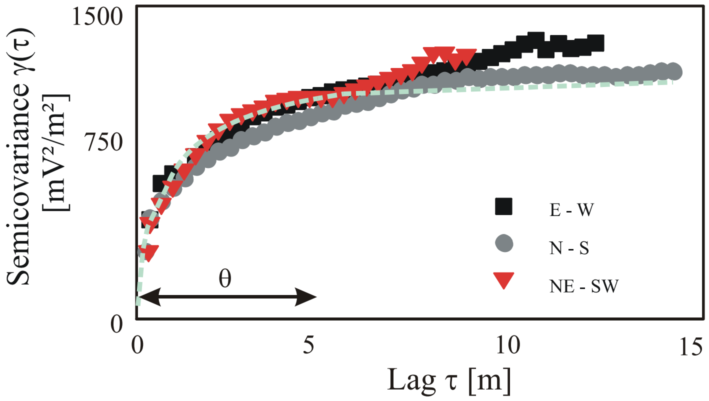

Fig. 11: Variogram in 3 directions (E-W, NS, NE-SW) of the bridge

semicovariance $\gamma(\tau)$ as well on the autocorrelation function $\rho(\tau)$. Therefore we have to use the above described indicator approach.

For this purpose, the quantils of the cumulative distribution function of the measurements have been evaluated and used as thresholds z_k of the indicator approach (equation 3). For each threshold the correlation length has been evaluated. It can clearly seen in Fig. 12 that the correlation length of the lower and the upper extremes of the cdf can be neglected. The biggest correlation length was detected for a threshold of 50% of the cdf. If one generates a Gaussian random field and evaluates the indicator correlation distances, one can observe the same behaviour as shown in Fig. 12. A deeper discussion is presented in Chiles & Delfiner [4].

3.3 Interpretation of the results

Looking at the results of investigations on the spatial variability of corrosion properties of reinforced concrete, it is difficult to compare it with the above presented results. The parking areas have a smaller correlation length of the potential (θ_{parking} = ~ 3 m) than the driving area (θ_{driving} = ~ 10 m). These values are between the correlations length of the bridge (θ_{bridge} = ~ 5 m).

Looking at the extreme values of the distribution in Fig. 12, one can identify low correlation lengths. These low correlation lengths are indicators for small areas. This can be identified in Fig. 4 and Fig. 5 because the lighter zones are the corroded areas, which have a potential that belongs to the lower extremes of the cdf in Fig. 12. In addition to this, one can also look at Fig. 4 and Fig. 5 and focus on the mean value with the largest correlation length. These areas in Fig. 4 and Fig. 5 are bigger and this can be traced back to a longer correlation length in comparison to the extreme values of the cdf.

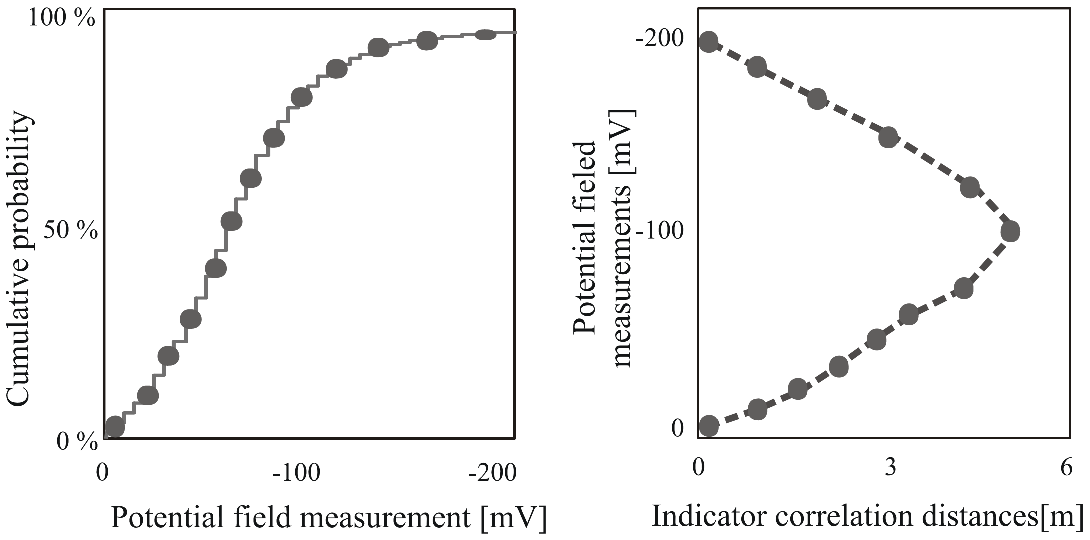

Fig. 12: Indicator correlation distances for quantils of the cumulative distribution function of the measurements of the bridge

It can be concluded from the comparison between the calculated element size (θ_{parking} = ~ 3 m; θ_{driving} = ~ 10 m; θ_{bridge} = ~ 5 m) and the indicated element size from literature (Tab. 1) that the element size can be chosen bigger than 1m. This means that the measurement grid can also be bigger than 0.25 x 0.25 m. This assumption has to be corroborated with a separate evaluation of the spatial variability of potential mapping and the evaluation of the spatial variability of corrosion processes. The measured values can be allocated to different elements and evaluated for each element separately. Furthermore additional measurements like chloride profiles can be determined depending on the spatial variability of the potential field. So the evaluation of potential fields become more accurate and the maintenance planning can be adapted more precisely.

4 Summary and Outlook

The spatial variability of potential fields was evaluated on the basis of measurements at two reinforced concrete structures. Comparable correlation lengths for parking and driving areas were evaluated and compared to published results of other investigations. The results of the spatial variability have proven the spatial Gaussian behaviour of potential fields. This enables the use of Gaussian random fields for further investigations and modelling approaches, which just need the assumption of the mean value, variance and correlation function [4]. To verify this conclusion further evaluation of potential mapping of larger area structures are needed.

The evaluation of spatial variability can provide necessary information for determining the spatial extend of inspection or the optimal number of samples that should be taken. It allows predicting the proportion or percentage of the surface area that shows concrete deterioration. This information can facilitate the optimization of repair or maintenance strategies for concrete structures, based on the percentage of the structure surface that shows external signs of deterioration. The calculation with spatial variability reflects the actual situation more realistically and has the flexibility to implement spatial differences of the structural properties. The approach with spatial variability provides more differentiated information about the condition of the structure and so the service life time can be predicted more accurately.

The advantage of potential mapping is that it provides two-dimensional information. So the time and effort are less than obtain data of the chloride migration coefficient or of chloride profiles. Further work will focus on developing models for updating the probability of spatially distributed corrosion based on potential mapping and corrosion modelling. This can provide support in maintenance planning and maintenance strategies for corroding reinforced structures.

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