Probability of Detection of Potential Mapping and its Impact on Service Life Prediction

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ABSTRACT: The potential mapping method is the most suitable inspection method to detect ongoing corrosion in reinforced concrete structures. The accuracy of this measurement method is expressed by the Probability of Detection. In combination with potential mapping data gained from inspection the information about the Probability of Detection delivers the needed information to update the service life prediction of reinforced concrete structures. Potential mapping data includes information about the temporal development and the spatial variability of corrosion. In this way, the condition of existing structures can be evaluated more realistic. This paper presents a case study for updating the service life prediction with concrete cover data and potential mapping.

1. INTRODUCTION

The durability of reinforced concrete structures which are exposed to de-icing salt or seawater can be impaired due to chloride induced corrosion of the reinforcement. The deterioration process starts with the depassivation of the rebars followed by local loss of cross section and cracking respectively spalling of the concrete cover. If no maintenance actions are executed the serviceability cannot be ensured any longer.

Therefore, the probabilistic service life prediction of reinforced concrete structures focuses the so called corrosion initiation phase. The initiation model provided by the fib Model Code for Service Life Design [Schießl et al. 2006] describes the time-dependent probability that reinforcement is depassivated. It is a transport based model and considers when a critical corrosion inducing chloride content at the depth of the reinforcement is reached in dependence of the concrete characteristics and chloride impact.

Inspection data from the considered structure can be used to update the service life prediction and to reduce the uncertainties associated with the probabilistic model. The most important inspection methods are the determination of the concrete cover and the detection of corroding areas by the so called potential mapping [ASTM 2009, DGZfP 2014]. Both measurement methods are executed non-destructively and deliver spatial information about the structure.

While the concrete cover inspection data are of a quantitative nature the information regarding potential mapping are qualitative data; the outcome is corrosion yes or no. Due to the fact that the concrete cover is also an input parameter of the probabilistic model the update is pursued by recalculating the depassivation probability with real data gained during inspection.

The incorporation of the qualitative potential mapping data into the probabilistic service life prediction is performed by applying Baye's rules (equation 1)

$$P(C|I) = \frac{P(I|C) \cdot P(C)}{P(I)} \qquad (1)$$

where:

C = Condition
I = Inspection.

The Bayesian approach combines pre-existing knowledge coming from service life prediction, Pr(condition), with inspection data represented by the likelihood function Pr(inspection│condition) and allows updating the prior knowledge. In the case of corrosion deterioration the likelihood function corresponds to the expression Pr(potential mapping results │ corrosion condition state) also known as the Probability of Detection.

1.1 Probability of Detection of potential mapping

An essential part of the evaluation of the capability for a non-destructive testing system (NDT) is defined as the probability of detecting a defect with a particular size under specified inspection condition and defined procedure. The accepted statistical parameter of quantifying this definition is the Probability of Detection (POD). The POD is usually expressed as a function of flaw size according to the physical background of the testing system. The associated defect size for corrosion detection is the anode area ‘a’.

One of the probabilistic methods for analyzing reliability data and producing POD-curves as a function of the flaw size is called “hit/miss” data [Berens 1989 - MIL-HDBK-1823A 2009] using the discrete response of the NDT-system. The NDT results are recorded in term whether the flaw is detected or not.

Kessler [Kessler 2015] evaluated POD-curves based on a numerical approach. Figure 1 shows two POD-curves in dependence of the grid size considering a concrete resistivity of 400 Ωm.

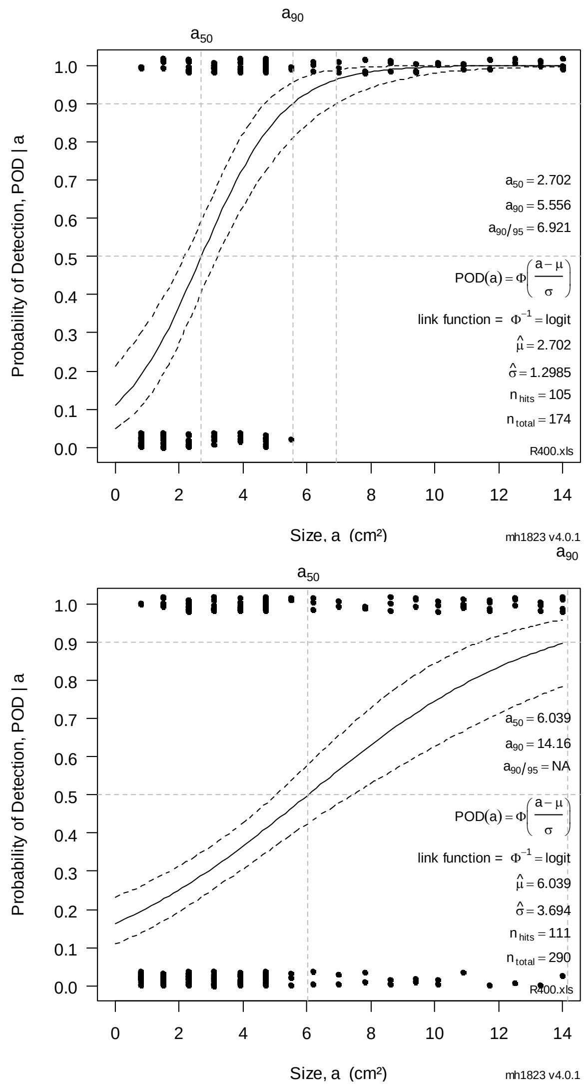


Figure 1: POD in dependence of grid size; 15 x 15 cm² (above), 25 x 25 cm² (below); concrete resistivity 400 Ωm [Kessler 2015].

With increasing grid size decreases the Probability of Detection. Choosing a grid size of 15 x 15 cm² an anode area with a size of 2.7 cm² has a 50 percent probability of detection. This defect size increases until 6.0 cm² when using a grid size of 25 x 25 cm². The POD of potential mapping is primarily determined by the used grid size. Kessler (2015) presents additional POD curves of potential mapping in dependence of more influencing parameters.

2 CASE STUDY

In this case study it is presented a procedure to update the a-priori service life prediction with inspection data considering quantitative concrete cover data and qualitative potential mapping results.

2.1 Structure

The structure built in 1961 is an abutment wall close to a highly frequented road in the city center of Munich. The exposure condition is characterized by a high chloride impact during winter times in combination with drying-wetting cycles. As a consequence chloride induced corrosion is the dominant degradation mechanism.

The abutment wall is on each side more than 200 m long with a varying height of 0.5 until 5 m. For a better overview this paper focuses on one segment with a size of 12 x 5 m², see Figure 2.

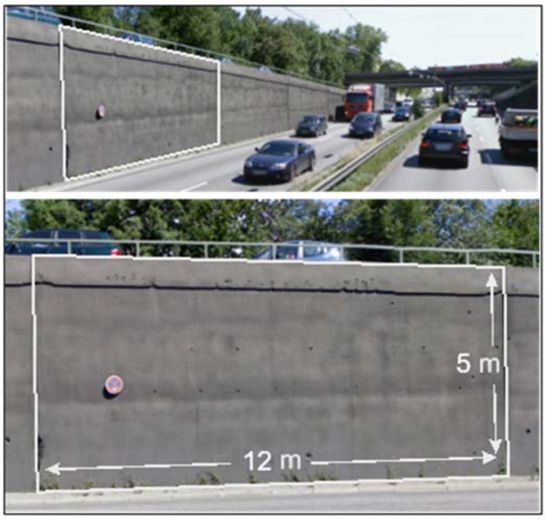


Figure 2: Selected part of the structure.

The a-priori depassivation probability is calculated with the initiation model presented in the fib Model Code for Service Life design [Schießl et al. 2006], equation 2 and Table 1.

$$p_f = \left\{ C_{\text{crit}} - C_{\text{S},\Delta x} \cdot \left[1 - erf\left(\frac{d_c - \Delta x}{2\sqrt{D_{RCM,0}\, k_e\, k_t \cdot \left(\frac{t_0}{t}\right)^a \cdot t}} \right) \right] \leq 0 \right\} \quad (2)$$

Table 1: Input parameters.

Par.	*Unit*	*Distr.*	*Values*
C_{crit}	*[M.-%/z]*	*beta* $0 \leq C_{crit} \leq 2$	*0.6; 0.15*
$C_{S,\Delta x}$	*[M.-%/z]*	*lognormal*	*2.73; 1.23*
d_c	*[mm]*	*lognormal*	*40; 13*
Δx	*[mm]*	*beta* $0 \leq \Delta x \leq 50$	*8.9; 5.6*
$D_{RCM,0}$	$[10^{-12} m^2/s]$	*normal*	*498.3; 99.7*
T_{real}	*[K]*	*normal*	*282; 3*
T_{ref}	*[K]*	*const.*	*1*
b_e	*[K]*	*normal*	*4800; 700*
t_0	*[a]*	*const.*	*0.0767*
t_{insp}	*[a]*	*const.*	*47*
a	*[-]*	*beta* $0 \leq a \leq 1$	*0.3; 0.12*

No information was available about the concrete composition. In consideration of the materials used commonly in this construction period it is assumed a Portland cement with water-binder ratio 0.55. The selected input parameters for the service life prediction are in accordance with reference [Schießl et al. 2006]. Figure 3 shows the a-priori depassivation probability calculated with STRUREL.

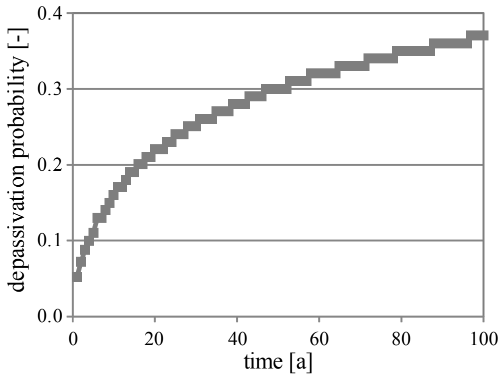


Figure 3: a-priori depassivation probability.

At the time of inspection the segment was 47 years old. The whole surface shows a depassivation probability of 30 % during time of inspection.

2.2 Inspection outcome

The inspection results of the concrete cover with grid size of 0.25 x 0.5 m², Figure 4, as well as for the potential mapping with a grid size of 0.25 x 0.25 m², Figure 5, is illustrated in the following Figures. During the visual inspection neither cracks nor spalling were visible.

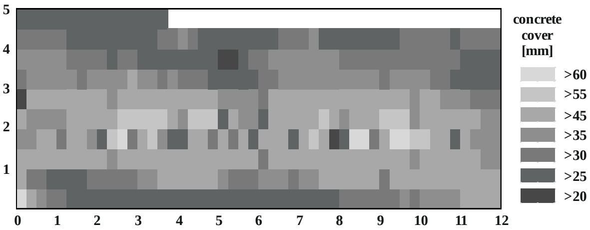


Figure 4: Inspection results: concrete cover.

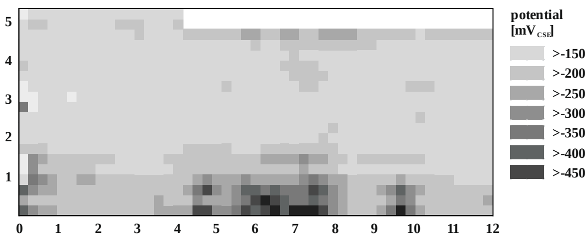
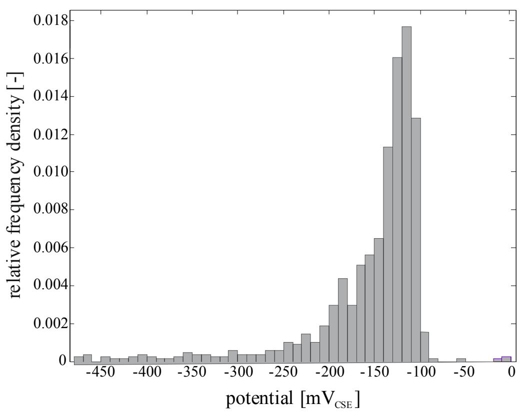


Figure 5: Inspection results: potential mapping.

The concrete cover scatters in a range of 25 until 70 mm. In a median strip the concrete cover is higher than at the bottom or in the height of the segment. No critical parts with a very low concrete cover are identifiable.

The potential mapping data show noticeable results with low potential differences in combination with a pronounced potential gradient at the bottom of the segment (longitude 4.7 m; 5.75-7.75 m and 9.75 m). These are indicators for ongoing corrosion processes. Over the heights of 1.5 m the corrosion probability approaches zero.

The statistical evaluation of the potential mapping results are shown in Figure 6.



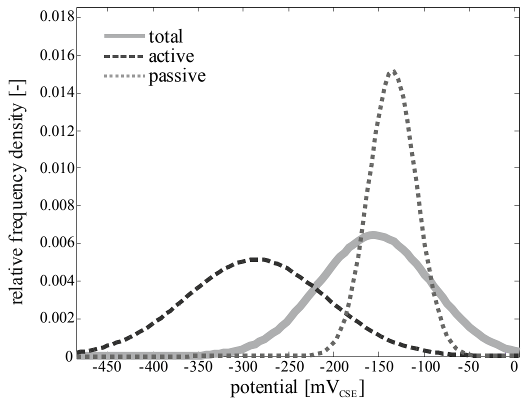


Figure 6: Histogram of the potential differences for active and passive reinforcement, as well as their combined PDF (gray).

It can be concluded from the statistical evaluation of the potential mapping results that potentials lower than -220 mV$_{CSE}$ are an indicator for corrosion. The distribution of the reinforcement being probably passive does not exceed a value below -220 mV$_{CSE}$. Potential values more positive than -100 mV$_{CSE}$ belong clearly to passive reinforcement. In a range between -220 mV$_{CSE}$ $\leq$ -100 mV$_{CSE}$ the active and the passive distribution overlap each other, therefore, values in this range can be associated to active as well as to passive distribution.

2.3 Updating of service life prediction

The updating of the service life prediction can concern two dimensions; the temporal and spatial dimension. Due to the fact that the inspection data after a service life of 47 years is considered the temporal aspect is covered. The spatial aspect is taken into account with a subdivision of the surface into elements with a size corresponding to the grid size. The spatial variability within the elements is neglected.

2.3.1 Updating with measured concrete cover

For each element the updating of the service life procedure is pursued with the measured concrete cover data. The resulting depassivation probability is shown in Figure 7. The element size is 0.25 x 0.5 cm².

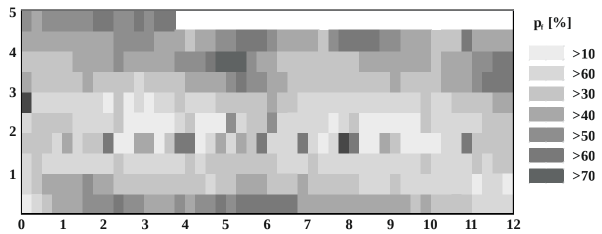


Figure 7: Updated depassivation probability with concrete cover data.

Due to the procedure of updating the appearance of the updated depassivation probability with concrete cover data is comparable to the concrete cover results itself. Instead of the concrete cover value each element is connected to a depassivation probability. Parts with a depassivation probability over 40 % are in the area below as well as in the height.

The advantage of the type of illustration is that parts of high depassivation probabilities can be located directly.

2.3.2 *Updating with potential mapping*

As already mentioned the update of the service life prediction with the qualitative information coming from potential mapping can be realized by applying Bayes' approach. Both information the a-priori depassivation probability as well as the inspection results are subjected to uncertainty.

The probability of corrosion given that it corrodes in dependence that corrosion will be indicated follows:

$$P(C|I) = \frac{P(I|C)\cdot P(C)}{P(I|C)\cdot P(C)+P(I|\bar{C})\cdot P(\bar{C})} \quad (3)$$

The probability of no corrosion given that the reinforcement is passive and no corrosion will be detected follows:

$$P(\bar{C}|\bar{I}) = \frac{P(\bar{I}|\bar{C})\cdot P(\bar{C})}{P(\bar{I}|\bar{C})\cdot P(\bar{C})+P(\bar{I}|C)\cdot P(C)} \quad (4)$$

The potential field is measured with a grid size of 0.25 x 0.25 m². For the update of the service life prediction the POD-curve according to Figure 1 (grid size 0.25 x 0.25 m²) is used.

A critical defect is defined to express the probability of detection in their dependence. The critical defect size is determined as a_{crit} = 2 cm². Following Figure 1 the POD(a_{crit}) is approximately 0.25. The Probability of False Alarm is assumed to be $Pr(I|\bar{C})$ = 5 %.

Figure 8 shows the development of the service life prediction after indication and no indication of corrosion. The spatial variability is neglected. If corrosion is indicated the depassivation probability increases to 59 %. In contrast to the case of no corrosion is detected the depassivation probability decreases to 18 %.

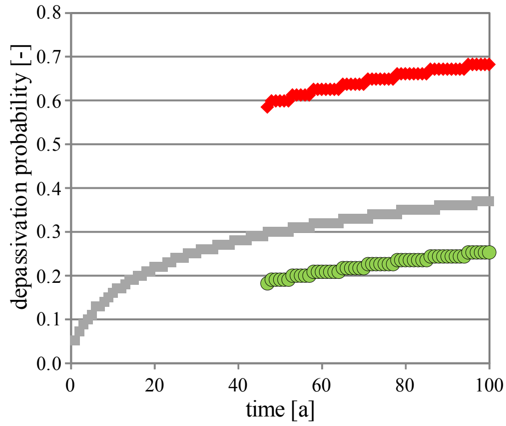


Figure 8: Update of the service life prediction for considering POD(a_{crit}) for case I "Indication of corrosion" (red) and case II "No indication of corrosion" (green).

In the next step the measured potential field is integrated. A so called threshold potential is defined which divides the whole measured potential differences into indication of active and indication of passive reinforcement. If the threshold potential is too positive non-corroding areas will be maintained unnecessarily. In contrast if the threshold potential is too low, corroding areas are overlooked. So, the threshold potential is defined with the 80 % quantile of the normal distribution of the active reinforcement. The value is -220 mV_{CSE}, compare with Figure 6.

As a consequence of the defined threshold potential the corresponding Probability of Detection is 80 % and the complementing Probability of False Alarm approaches 0 %. This situation includes the probability that corroding areas will be overlooked but the Probability of

False Alarm is minimized. The following condition can be deduced:

$$P(I|C) = 0.8$$
$$P(\bar{I}|C) = 0.2$$
$$(P\bar{I}|\bar{C}) \approx 0.99$$
$$P(I|\bar{C}) \approx 0.01$$

The depassivation probability after the updating with concrete cover data is now updated with the potential mapping data by applying Bayes' rules, Figure 9. The element size corresponds to the grid size 0.25 x 0.25 m².

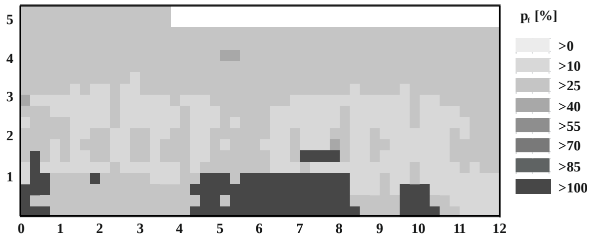


Figure 9: Updated depassivation probability with potential mapping.

The updated depassivation probability with concrete cover data and potential mapping data results in more differentiated information about the corrosion condition of the segment. High depassivation probabilities $p_f > 80$ % are located in the bottom of the segments (longitude 0-0.5 m, 4.25-8.25 m and 9.5-10.25 m). From a height of 1.75 m the depassivation probability is very low.

This effect can be explained by the type of chloride exposure. The segment is a vertical component and its chloride impact results from de-icing salt containing splash water due to the traffic during winter time. The splash water reaches only a certain height and so the chloride impact and as a consequence the chloride induced corrosion is more pronounced in the upper part of the segment.

Comparing the updating with concrete cover dated and with both inspection methods the result after updating with concrete cover and potential mapping allows a better distinction of the corrosion condition state. After the updating with concrete cover data no pronounced depassivation probability is noticeable. This is due to the type of gained information of both inspection methods. The concrete cover measurement describes indirectly the condition of the structure with the help of a probabilistic model. The concrete cover reflects only a part of the material resistance and does not provide information about the intensity and distribution of the exposure (chloride impact) or any inhomogeneity.

With increasing exposure time the potential mapping method gives indirectly information about the spatial variability of the chloride impact. The potential mapping results are connected directly to the condition of the structure.

In general the depassivation probability in the most striking areas is very high even though that POD(a_{crit}) is only 25 %. But the distinction between the distribution of the potential differences of the active and passive indicating reinforcement is very clear which enhance the final corrosion detection.

2.4 *Validation of updating*

During repair action on the structure the whole concrete cover is removed and the visual inspection of the reinforcement is pursued, see Figure 10.

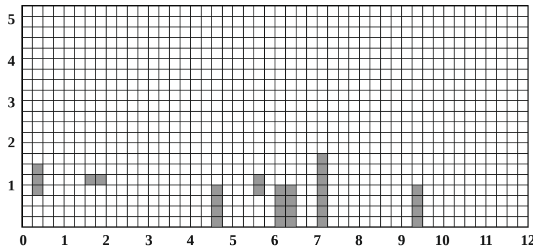


Figure 10: Visual inspection about the corrosion condition of the reinforcement (gray elements: loss of cross section).

The grey elements show corrosion appearance in form of roughening of the metal surface until a loss of cross section up to 50 %. Within the white elements no change of the reinforcement surface were detected.

Corrosion takes place in the left corner at a height of 1 m and at the longitude 4.5 m until

7.5 m until a height of 1.5 m. Over a height of 1.5 m no corrosion appearances were visible.

The comparison of the real corrosion condition with the predicted one shows that the predicted depassivation probability indicates more corroding areas than really exists. But the most important point is that no corroding areas were overlooked. The criteria for updating the service life with potential mapping data are on the safe side with regard to structural safety.

3 CONCLUSIONS

The maintenance of our aging infrastructure is one of the main tasks for engineers today. The probabilistic description and prediction of structure condition is a suitable tool to support this task.

This paper presents a case study of implementing the potential mapping data into the updating of the service life prediction. By subdividing the structural surface into elements related to the used grid size the spatial information about the deterioration process a maintained. Further inspection or repair action can be planned more precisely and economically.

But this approach considering the spatial variability of deterioration processes is rather simple. More effort is needed investigate the random fields modeling to consider spatial variability. There is a lack of information concerning the correlation length of those parameters which are governing the deterioration process. However, not only the deterioration process shows spatial dependencies also the measurement method itself can show a spatial characteristic.

Besides the concrete cover and the potential field it is often useful to measure additional parameters like chloride profiles etc.. This additional information can also be implemented into the updating process of the service life prediction.

4 REFERENCES

Schießl P, Bamforth P, Baroghel-Bouny, V, Corley G, Faber M, Forbes J, Gehlen C, et al. Model code for service life design. *fib bulletin 34*, 2006.

ASTM C876, 2009. Standards Test Method for Half Cell Potentials of Reinforcing Steel in *Concrete American Society for Testing and Materials*

DGZfP Merkblatt B3 2014. Elektrochemische Potentialmessungen zur Detektion von Bewehrungsstahlkorrosion (German)

Berens, Alan P. NDE reliability data analysis. ASM International. *Metals Handbook* Vol. 17 Ed. 9. 1989.

MIL-HDBK-1823A, *Department of Defense Handbook*, Nondestructive Evaluation System Reliability Assessment, 7. April 2009

Kessler, S.: The use of potential mapping in condition assessment and prognosis for reinforced concrete structures – Validation and application in service life management, *PhD thesis, Technische Universität München,* 2015 (German)