Approximation of the bridge deck diffusion coefficient and surface chloride concentration from field data

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Abstract. The aim of this work is to analyse the data from in-situ measurements performed on 5 reinforced concrete bridges built between 1937 and 1986, that are a part of the road network in the Czech Republic. The bridges were subjected to the field measurements in order to evaluate the ability of the concrete to protect the steel reinforcement from corrosion, namely the pH and the amount of water-soluble chlorides were evaluated on drilled core samples of concrete. Based on the actual chloride content, the diffusion coefficient and surface chloride concentration were determined. All the data were statistically summarized and the correlations among them were provided. The main focus of this study is to evaluate the non-proportional effect of the amount of chlorides per mass of concrete on the risk of corrosion initiation and to determine the unknown parameters of concrete – diffusion coefficient and surface chloride concentration, based on the numerical model of diffusion.

1. Introduction

Bridges in the Czech Republic are the typical constructions exposed to the combined effect of carbonation, chloride ingress and mechanical load. Such structures are prone to corrosion that threatens their durability and reduces the service life and bearing capacity.

The current design of typical structural elements with respect to exposure conditions is executed by the deemed-to-satisfy rules prescribed by EN 1992-1 and EN 206. Currently, the discussion and benchmarking on durability calculations based on these rules have been undertaken by the European technical committees and fib Commissions. It is intended to replace them with a performance-based design approach (PBD) in future standards [1] –[4]. An important part of preparation for PBD is analysis of the durability of existing structures under service in order to improve the authenticity of available numerical tools. Some of them are described for instance in [5] – [12].

Even though the physical law for the analysis of the penetration of agents inducing steel reinforcement corrosion (such as chlorides or carbon dioxide) are known, the modelling still contains a lot of unknowns, especially in case of heterogeneous material (such as concrete). It is worth to mention that even more questions arise when consider the selection of input parameters for models. Of course, there are recommendations in codes [2], [4], [13], [14]; however, the fidelity of such recommendations to every structure are of question. Thus, interpretation of the results of such durability analysis needs to be taken with care. The simulation results, such as length of service life, might be used in case of comparison of different scenarios and selection of the most durable one. The actual time shall not be extracted from the analysis by itself [13].
Numerical modelling of chloride penetration might be simplified using deterministic one dimensional numerical diffusion model called Crank’s solution applied by Collepardi [15]:

\[ C_{z,t} = C_0 \left[ 1 - \text{erf} \left( \frac{z}{\sqrt{4 D_c t}} \right) \right], \quad (1) \]

where:
- \( C_{z,t} \) – concentration of chlorides [% by mass of concrete],
- \( C_0 \) – concentration of chlorides [% by mass of concrete] at the surface layer of concrete,
- \( D_c \) – apparent diffusion coefficient of chloride ions in concrete [m²·s⁻¹],
- \( t \) – chloride exposition time [s],
- \( z \) – depth of the reinforcement (concrete cover) [m].

The more elaborated model that considers random scatter of input parameters was used in [8], [14] and punctual model with respect to cracking of steel reinforcement protection, such as 2D model with crack consideration, in [9]. Some of the models imitate heterogeneity, example of such mesoscopic model is presented in [16]. The more detailed model is used, the more demanding the calculation in terms of the computer hardware and simulation time is, and the total cost of analysis increases. Thus, the balance between the fidelity and quality of the model and input parameters is the challenge for researchers specialized in areas related to modelling of the steel corrosion in concrete.

With respect to the matters mentioned above, the attention shall be focussed, beside of the improvement of the numerical models, also on the improvement of recommendations for the input parameters used in the models in order to provide effective, yet reliable models to the engineering community.

In this paper, the data from regular inspections of highway bridges in the Czech Republic are analysed with respect to the corrosion related durability aspects and modelling of reinforced concrete. Some of the bridges were already analysed in the previous works focusing on the critical value of chlorides and pH to initiate the corrosion and on estimation of surface chloride concentration, however, the diffusion coefficient was not determined yet, see e.g. [17].

The attention is concentrated to a simple 1D model of the chloride penetration, where the diffusion coefficient of chloride penetration \( D_c \), time and the surface chloride concentration \( C_0 \) are of interest – eq. (1).

Since the limit state definition is an important part of the evaluation, the effect of carbonation on the chloride threshold to initiate the corrosion is of high importance [17], [18]. It needs to be noted that the effect of the pH change related to the carbonation of concrete is usually not taken into account in the publications from this area. Thus, further evaluation of the common effect of carbonation and chloride presence is necessary.

Special attention is paid to the chloride concentration profiles and to determination of the unknown parameters of concrete – diffusion coefficient and surface chloride concentration, based on the numerical model of diffusion.

2. Scope

The subjects of the inspection and subsequent analysis are 5 highway bridges in the Czech Republic. The bridges are marked by numbers: no. 54-040 over a stream that was built in 1937 and inspected in 2014, no. 55I-026a over a local way built in 1976 and inspected in 2014, no. 55I-030 over a river built in 1953 and inspected in 2015, no. 55-033 over a river built in 1963 and inspected in 2016 and no. 57-039 also over a river built in 1985 and inspected in 2013.

The procedure of the selection of corrosion related data and their processing are discussed in the section Experimental methodology. The process of evaluation of data is shown in the section Numerical analysis of the bridge 55I-030 and overall results are discussed in the section Discussion and conclusions. The comprehensive results for the other selected bridges are given in the Appendices.
3. Experimental methodology
The corrosion related data were collected during the regular inspections of the highway bridges under service that are in the portfolio of Directorate of Highways and Motorways of the Czech Republic. The representative locations of girders, abutments, bearing seats or joints were selected and concrete cores were sampled. In each location, the samples were taken from three different depths of 0–10, 10–20 and 20–30 mm from the concrete surface.

Subsequently, the value of pH and the amount of water-soluble chlorides were measured in water leaches in laboratory [20]. Based on these parameters, the diffusion coefficient and surface chloride content were determined. The ratio between the concentrations of Cl\(^-\) and OH\(^-\), that indicates the ability of concrete to protect the reinforcement, was determined in previous work [17]. In the other words, the higher the ratio is, the higher is the potential risk of corrosion initiation and propagation. As a critical value of the ratio c(Cl\(^-\))/c(OH\(^-\)) = 0.6 can be considered [21].

3.1. Calculation of the diffusion coefficient and surface chloride concentration
The lacking parameters, that are, in this case, the diffusion coefficient \(D_c\) and the chloride concentration on the surface \(C_0\), were determined iteratively by the analogy to the least square method. Regression analysis served for minimizing the sum given by equation (2) [22]:

\[
S_j = \sum_i^N \left( \Delta C_{(i)}^2 \right) = \sum_i^N \left( C_{m(i)} - C_{c(j,i)} \right)^2,
\]

where:
- \(S_j\) – sum of the squares in the \(j\)-th iteration [(% by mass)\(^2\)],
- \(N\) – number of layers in profile,
- \(\Delta C_{(i)}\) – difference between the measured and calculated concentration of chlorides in the \(N\)-th layer [\% by mass of total cementitious materials],
- \(C_{m(i)}\) – measured concentration of chlorides [\% by mass of total cementitious materials],
- \(C_{c(j,i)}\) – calculated concentration of chlorides in the \(j\)-th step iteration and the \(i\)-th layer [\% by mass of total cementitious materials].

Chloride concentration can be calculated using the equation (3) also [19], [23]. For the first iteration, the diffusion coefficient \(D_c\) and surface concentration of chlorides \(C_0\) are selected. The time \(t\) corresponds to the exposure time to the chloride mode.

\[
C_{z,t} = C_0 \left[ 1 - \frac{2}{\sqrt{n}} \sum_{n=0}^{14} (-1)^n \left( \frac{z}{\sqrt{n+1}} \right)^{2(n+1)} \right],
\]

where the symbols have been already explained in relation to equation (1) and \(n\) is the number of the polynomial set.

However, due to the approximation of the chloride profile by the equation (3), that does not take into account the aging of the concrete over the time, the value of the diffusion coefficient can be overestimated.

4. Numerical analysis of the bridge 55I-030
All the investigated bridges were subjected to the numerical analysis leading to the estimation of diffusion coefficient and surface chloride concentration from the measured data. For the purpose of the paper, the numerical procedure is described in detail in case of one of the bridges. The subject of the example is a single pole bridge no. 55I-030, which transfers the road I/55I across the Dřevnice river in the centre of Otrokovice [20]. The bridge was built in 1953 and diagnostic drilling was executed in 2015, so the exposure time is 62 years.
The layout of the bridge is available in the Figure 1. The lower structure is composed of two monolithic concrete supports with short parallel wings installed in the upper part of the abutments. There is stone paving in concrete bed that creates relatively steep slope in front of the abutments along the entire length of the retaining walls. The horizontal load bearing structure is made of 16 prefabricated prestressed “T” beams with the span of 28 m. The beams are based on steel bearings.

The selected points of the drilled cores for aforementioned chemical analysis are also shown in the Figure 1 and described in Table 1. It should be noted that for bridge no. 55I-030 in Figure 1, there are 11 sample cores (points from 1 to 11). There are also 4 sites where the repairing concrete overlay has been applied (points 12 to 15).

Figure 1. Front views of the abutments and the scheme of the bridge including sample core spots. Red triangles with black numbering represent core positions and red numbers represent the number of girders.

From Table 1 suitable chloride profiles, that are characterized by decreasing value of chloride concentration as shown in Figure 2, were selected. The chosen samples are given in Table 2. Approximations of the chloride profile are shown in Figure 3.
Table 1. Chloride profiles and concrete strengths sampled at bridge no. 55I-030 (built in 1953, inspected in 2015, over a river).

| ID     | No. | Location                                                      | Chloride profile [%Cl] | Concrete | Strength [MPa] |
|--------|-----|---------------------------------------------------------------|------------------------|----------|----------------|
| 55I-030-1 | 1   | 1<sup>st</sup> abutment, middle part under bearing seat       | 0.02 0.02 0.02         | Unsuitable | C45/55 55.3    |
| 55I-030-2 | 2   | 2<sup>nd</sup> abutment, right under bearing seat              | 0.50 0.55 0.38         | Unsuitable | C45/55 55.3    |
| 55I-030-3 | 3   | 2<sup>nd</sup> abutment, left under bearing seat               | 0.23 0.16 0.16         | Suitable  | C45/55 55.3    |
| 55I-030-4 | 4   | 2<sup>nd</sup> cross girder, between 2<sup>nd</sup> and 3<sup>rd</sup> girder | 0.03 0.01 0.01         | Suitable  | C40/50 55.5    |
| 55I-030-5 | 5   | 4<sup>th</sup> cross girder, between 9<sup>th</sup> and 10<sup>th</sup> girder | 0.01 0.01 0.07         | Unsuitable | C40/50 55.5    |
| 55I-030-6 | 6   | Longitudinal joint between 9<sup>th</sup> and 10<sup>th</sup> girder, 1<sup>st</sup> abutment | 0.02 0.02 0.01         | Suitable  | C40/50 55.5    |
| 55I-030-7 | 7   | Longitudinal joint between 4<sup>th</sup> and 5<sup>th</sup> girder, 1<sup>st</sup> abutment | 0.03 0.01 0.02         | Unsuitable | C40/50 55.5    |
| 55I-030-8 | 8   | Girder no. 4, 1<sup>st</sup> cross girder                     | 0.04 0.03 0.02         | Suitable  | C45/55 55.2    |
| 55I-030-9 | 9   | Girder no. 8, 2<sup>nd</sup> abutment                          | 0.01 0.02 0.02         | Unsuitable | C45/55 55.2    |
| 55I-030-10 | 10  | Girder no. 12, half of span of the girder                      | 0.03 0.02 0.02         | Suitable  | C45/55 55.2    |
| 55I-030-11 | 11  | Girder no. 14, 2<sup>nd</sup> abutment                         | 0.07 0.05 0.02         | Suitable  | C45/55 55.2    |

Note: Selected sample locations are marked in the bridge scheme in Figure 1.

Figure 2. Graphical representation of chloride profiles from Table 1. Left – unsuitable profile, right – suitable profile.
Table 2: Calculated surface concentration of chlorides $C_0$ and diffusion coefficient $D_c$ for selected suitable samples.

| ID      | pH       | $c(\text{Cl}^-)/c(\text{OH}^-)$ | Surface concentration | Diffusion coefficient |
|---------|----------|-------------------------------|-----------------------|----------------------|
|         | 0-10 [mm]| 0-10 [mm] | 10-20 [mm] | 20-30 [mm] | 10-20 [mm] | 20-30 [mm] |
| 55I-030-3 | 11.64  | 11.65  | 11.70   | 0.10   | 0.16   | 0.16   | 0.238 | 6.501E-13 |
| 55I-030-4 | 11.11  | 11.08  | 11.70   | 0.08   | 0.01   | 0.01   | 0.037 | 8.025E-14 |
| 55I-030-6 | 11.51  | 11.55  | 11.69   | 0.14   | 0.02   | 0.01   | 0.024 | 3.443E-13 |
| 55I-030-8 | 11.69  | 11.54  | 11.76   | 0.06   | 0.03   | 0.02   | 0.046 | 2.748E-13 |
| 55I-030-10 | 11.50 | 11.57  | 11.74   | 0.04   | 0.02   | 0.02   | 0.031 | 5.330E-13 |
| 55I-030-11 | 11.75 | 11.76  | 11.79   | 0.06   | 0.05   | 0.02   | 0.087 | 1.347E-13 |

Figure 3. Approximation of the chloride profiles used for calculation of the surface concentration of chlorides $C_0$ and diffusion coefficient $D_c$.

The values of chloride concentration of every suitable sample were approximated as shown in Figure 3 and diffusion coefficient and surface chloride content were computed. The approximated curve is based on the determined diffusion coefficient. The next graph (given in Figure 4) is constructed in order to show the connection between individual data points of chloride profiles and the curve fitted...
among the data points. Thus, the concentration of chloride ions in three evaluated profiles and diffusion coefficient are displayed in Figure 4. It is worth mentioning that the source data are given in two tables (Table 1 and 2) including approximated surface chloride concentration values.

Figure 4. The chloride profile and calculated diffusion coefficient $D_c$ for suitable samples of the bridge no. 55I-030.

It can be seen that the trend of the ratio between chloride concentration and the diffusion coefficient is not proportional. It might appear, that if there is a higher concentration of chloride ions, the diffusion coefficient value should be higher. The assumption might be that if more chlorides got into the construction over the time then the concrete might be less resistant to chloride ingress and the diffusion coefficient is higher. Since the diffusion process is more complex phenomenon and the chloride ingress depends also on the surface concentration, temperature, moisture, type properties of the concrete, age of the construction etc., it is not that simple [7]. Because of this information, the results were divided into categories based on the class of the concrete represented by compressive strength. As a satisfactory result would be considered the values of diffusion coefficient in the same decimal level. Values of the diffusion coefficient for the class C45/55 range between $0.8 \times 10^{-13}$ and $6.5 \times 10^{-13}$ [m²s⁻¹]. The similar trend is visible also in the bridges 54-040 and 57-039. The bridge 55I-026a has variation of the diffusion coefficient within one class up to 40 percent. Unfortunately, authors do not have access to the strength class of the bridge 55-033. Thus, results from four bridges might be compared. The resulting values and respective graphs are given for the four bridges in the Appendices.

5. Discussion and conclusions

The article is focused on the analysis of data related to corrosion measured on 5 existing constructions in the Czech Republic. The numerical analysis is shown on one specific bridge (no. 55I-030) in detail and the results of the remaining bridges are given in the appendices A – D. Based on the provided data of concentration of chlorides, suitable samples were selected and the initial value of surface concentration and diffusion coefficient were estimated.

The diffusion coefficient was determined for every suitable sample from the approximation of three measured values by measurements. Difference in the estimation of the diffusion coefficient in specific concrete classes in the level of decimal place, that have been found in three bridges from four, seems to be unacceptable. The difference in case of one bridge (55I-026a) have the difference up to 40 percent which might be acceptable due to the effects of natural variation of concrete properties and environmental conditions affecting the measurements.

Based on the visual results, in this case, it cannot be proved that the diffusion coefficient is correlated to the concentration of chloride ions, nor the type of the concrete. Thus, it can be concluded that for the successful determination of the diffusion coefficient, three measured values are not sufficient; hence,
the approximation and the subsequent analysis is burdened with a numerical error. The above mentioned applies also to the estimation of surface chloride concentration values. The recommended value for more precise determination of diffusion coefficient is 5 or 6 measurements for every drilled core.

The visual comparison of the relationship between the concrete class and diffusion coefficient was used to evaluate the quality of approximation. Proposed procedure with quantified error analysis deserves further evaluation in the future research in order to be used as the tool for the evaluation of the quality of chloride profile data.

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Appendix A  Bridge 54-040 (built in 1937, diagnostics in 2014, over a stream).

| ID  | No. | Location | Chloride profile [%Cl-] | Concrete Strength [MPa] |
|-----|-----|----------|-------------------------|-------------------------|
| 54-040-1 | 1 | 1st abutment, left, bottom part | 0.04 0.04 0.03 | Suitable C8/10 10.2 |
| 54-040-2 | 2 | 1st abutment, right, bottom part | 0.11 0.06 0.04 | Suitable C8/10 10.2 |
| 54-040-3 | 3 | 1st abutment, left under bearing seat | 0.22 0.28 0.26 | Unsuitable C8/10 10.2 |
| 54-040-4 | 4 | 1st abutment, right, last cross girder | 0.23 0.37 0.32 | Unsuitable C8/10 10.2 |
| 54-040-5 | 5 | 2nd abutment, left, bottom part | 0.04 0.03 0.03 | Suitable C8/10 10.2 |
| 54-040-6 | 6 | 2nd abutment, middle part, bottom | 0.07 0.06 0.06 | Suitable C8/10 10.2 |
| 54-040-7 | 7 | 2nd abutment, left under bearing seat | 0.11 0.14 0.18 | Unsuitable C8/10 10.2 |
| 54-040-8 | 8 | 2nd abutment, middle part under bearing seat | 0.14 0.11 0.17 | Unsuitable C8/10 10.2 |
| 54-040-9 | 9 | girder no. 1 (2nd cross girder) | 0.16 0.04 0.05 | Unsuitable C16/20 22.4 |
| 54-040-10 | 10 | girder no. 2 (2nd cross girder) | 0.04 0.04 0.03 | Suitable C16/20 22.4 |
| 54-040-11 | 11 | girder no. 3 (2nd cross girder) | 0.03 0.03 0.02 | Suitable C16/20 22.4 |
| 54-040-12 | 12 | girder no. 4 (2nd cross girder) | 0.02 0.02 0.03 | Unsuitable C16/20 22.4 |
| 54-040-13 | 13 | girder no. 5 (2nd cross girder) | 0.03 0.02 0.01 | Suitable C16/20 22.4 |

| ID  | pH | c(Cl-)/c(OH-) | Surface conc. [%Cl-] | Diffusion coefficient [m.s²] |
|-----|----|---------------|----------------------|----------------------------|
| 54-040-1 | 10.35 | 2.64 | 6.72 | 0.044 | 9.94E-13 |
| 54-040-2 | 10.47 | 5.23 | 15.55 | 0.131 | 1.05E-13 |
| 54-040-5 | 10.48 | 1.8 | 1.27 | 0.041 | 8.03E-13 |
| 54-040-6 | 10.03 | 8.81 | 17.15 | 0.071 | 2.56E-12 |
| 54-040-10 | 8.68 | 116.8 | 98.02 | 0.044 | 1.00E-12 |
| 54-040-11 | 8.82 | 59.06 | 61.94 | 0.034 | 5.78E-13 |
| 54-040-13 | 8.79 | 74.47 | 27.18 | 0.036 | 1.17E-13 |
Appendix B Bridge 55I-026a (built in 1976, diagnostics in 2014, over a local way).

| ID     | No. | Location                                      | Chloride profile [%Cl-] | Concrete Strength [MPa] |
|--------|-----|-----------------------------------------------|-------------------------|-------------------------|
| 55I-026a-1 | 1   | 1st abutment, left, bottom part               | 0.06 0.05 0.04          | Suitable C12/15          |
| 55I-026a-2 | 2   | 1st abutment, right, bottom part              | 0.1 0.08 0.06           | Suitable C12/15          |
| 55I-026a-3 | 3   | 1st abutment, center part under bearing seat  | 0.22 0.27 0.3           | Unsuitable C12/15        |
| 55I-026a-4 | 4   | girder no. 4, 1st abutment                    | 0.05 0.07 0.07          | Unsuitable C40/50        |
| 55I-026a-5 | 5   | 2nd abutment, left, bottom part               | 0.02 0.02 0.02          | Unsuitable C12/15        |
| 55I-026a-6 | 6   | 2nd abutment, right, bottom part              | 0.03 0.03 0.02          | Suitable C12/15          |
| 55I-026a-7 | 7   | 2nd abutment, middle part under bearing seat  | 0.02 0.02 0.02          | Unsuitable C12/15        |
| 55I-026a-8 | 8   | 2nd abutment, right, bearing seat             | 0.02 0.02 0.02          | Unsuitable C12/15        |
| 55I-026a-9 | 9   | girder no. 8, 2nd abutment                    | 0.03 0.02 0.02          | Suitable C40/50          |
| 55I-026a-10 | 10  | girder no. 12, 2nd abutment                   | 0.04 0.03 0.02          | Suitable C40/50          |
| 55I-026a-11 | 11  | concrete patch, left above 1st abutment      | 0.19 0.13 0.13          | Suitable C30/37          |
| 55I-026a-12 | 12  | concrete patch, right above 2nd abutment     | 0.07 0.05 0.04          | Suitable C30/37          |

| ID     | pH | c(Cl-)/c(OH-) | Surface conc. [%Cl-] | Diffusion coefficient [m.s⁻²] |
|--------|----|---------------|----------------------|------------------------------|
| 55I-026a-1 | 9.06 9.31 9.15 | 78.88 37.51 42.4 | 0.065 1.02E-12 |
| 55I-026a-2 | 9.44 9.51 10.11 | 49.82 32.87 7.04 | 0.111 7.07E-13 |
| 55I-026a-6 | 8.84 8.75 8.73 | 51.42 63.26 62.86 | 0.034 1.20E-12 |
| 55I-026a-9 | 11.53 11.88 12.01 | 0.12 0.04 0.03 | 0.031 8.62E-13 |
| 55I-026a-10 | 11.63 11.95 12.07 | 0.35 0.19 0.16 | 0.046 4.46E-13 |
| 55I-026a-11 | 11.88 11.97 12.04 | 0.12 0.04 0.02 | 0.197 9.78E-13 |
| 55I-026a-12 | 11.17 11.28 11.85 | 0.67 0.35 0.02 | 0.077 5.67E-13 |
Appendix C: Bridge 55-033 (built in 1963, diagnostics in 2016, over a river).

| ID     | No. | Location                          | Chloride profile [%Cl-] |
|--------|-----|-----------------------------------|-------------------------|
|        |     |                                   | 0-10  | 10-20 | 20-30 |
| 55-033-1| 1   | 1<sup>st</sup> abutment, bearing seat, left | 0.21  | 0.24  | 0.23  | Unsuitable |
| 55-033-2| 2   | 1<sup>st</sup> abutment, bearing seat, middle part | 0.11  | 0.18  | 0.09  | Unsuitable |
| 55-033-3| 3   | 1<sup>st</sup> abutment, bearing seat, right | 0.08  | 0.11  | 0.09  | Unsuitable |
| 55-033-4| 4   | 4<sup>th</sup> support, bearing seat, left | 0.06  | 0.1   | 0.08  | Unsuitable |
| 55-033-5| 5   | 4<sup>th</sup> support, bearing seat, middle part | 0.02  | 0.02  | 0.02  | Unsuitable |
| 55-033-6| 6   | 4<sup>th</sup> support, bearing seat, right | 0.06  | 0.03  | 0.03  | Suitable  |
| 55-033-7| 7   | 2<sup>nd</sup> support, bearing seat, left | 0.02  | 0.01  | 0.01  | Suitable  |
| 55-033-8| 8   | 2<sup>nd</sup> support, bearing seat, middle part | 0.02  | 0.02  | 0.01  | Suitable  |
| 55-033-9| 9   | 2<sup>nd</sup> support, bearing seat, right | 0.01  | 0.01  | 0.01  | Unsuitable |
| 55-033-10| 10  | 3<sup>rd</sup> support, bearing seat, left | 0.04  | 0.03  | 0.02  | Suitable  |
| 55-033-11| 11  | 3<sup>rd</sup> support, bearing seat, middle part | 0.02  | 0.01  | 0.01  | Suitable  |
| 55-033-12| 12  | 3<sup>rd</sup> support, bearing seat, right | 0.01  | 0.01  | 0.01  | Unsuitable |
| 55-033-13| 13  | Girder, 2<sup>nd</sup> span, half of the span, left | 0.02  | 0.01  | 0.01  | Suitable  |
| 55-033-14| 14  | Girder 1<sup>st</sup> span, 3 m next to 1<sup>st</sup> support | 0.03  | 0.02  | 0.01  | Suitable  |
| 55-033-15| 15  | Girder, 1<sup>st</sup> span, middle part, front of 3<sup>rd</sup> abutment | 0.02  | 0.02  | 0.02  | Unsuitable |
| 55-033-16| 16  | Girder, 2<sup>nd</sup> span, middle part, 2<sup>nd</sup> abutment | 0.02  | 0.01  | 0.01  | Suitable  |
| 55-033-17| 17  | Girder, 2<sup>nd</sup> span, half of the span, middle part | 0.02  | 0.01  | 0.01  | Suitable  |
| 55-033-18| 18  | Girder, 2<sup>nd</sup> span, middle part, 3<sup>rd</sup> abutment | 0.02  | 0.02  | 0.02  | Unsuitable |
| 55-033-19| 19  | Girder, 3<sup>rd</sup> span, left side, next to 4<sup>th</sup> abutment | 0.22  | 0.09  | 0.06  | Suitable  |
| 55-033-20| 20  | Girder, 3<sup>rd</sup> span, left side, half of the span | 0.11  | 0.08  | 0.03  | Suitable  |

| ID    | pH  | c(Cl-)/c(OH-)| Surface conc. [%Cl-] | Diffusion coefficient [m.s<sup>-2</sup>] |
|-------|-----|--------------|----------------------|----------------------------------------|
| 55-033-6| 11.89 | 11.86 | 11.83 | 0.1 | 0.07 | 0.05 | 0.066 | 2.32E-13 |
| 55-033-7| 11.89 | 11.93 | 11.91 | 0.03 | 0.02 | 0.02 | 0.022 | 2.29E-13 |
| 55-033-8| 11.51 | 11.61 | 11.75 | 0.07 | 0.05 | 0.03 | 0.024 | 4.05E-13 |
| 55-033-10| 11.83 | 11.85 | 11.86 | 0.09 | 0.05 | 0.03 | 0.046 | 3.22E-13 |
| 55-033-11| 11.73 | 11.83 | 11.65 | 0.05 | 0.03 | 0.04 | 0.022 | 2.32E-13 |
| 55-033-13| 10.62 | 10.76 | 11.17 | 0.55 | 0.35 | 0.13 | 0.022 | 2.35E-13 |
| 55-033-14| 11.70 | 11.89 | 11.89 | 0.81 | 0.04 | 0.03 | 0.036 | 1.66E-13 |
| 55-033-16| 11.33 | 11.84 | 11.95 | 0.12 | 0.03 | 0.02 | 0.022 | 2.32E-13 |
| 55-033-17| 10.24 | 10.63 | 11.51 | 1.33 | 0.48 | 0.04 | 0.022 | 2.28E-13 |
| 55-033-19| 11.58 | 11.90 | 11.93 | 0.83 | 0.16 | 0.1  | 0.278 | 9.03E-14 |
| 55-033-20| 11.47 | 11.52 | 11.82 | 0.51 | 0.32 | 0.07 | 0.137 | 1.55E-13 |

Note: The type of the concrete was not measured.
Appendix D: Bridge 57-039 (built in 1985, diagnostics in 2013, over a river).

| ID    | No. | Location                                      | Chloride profile [%Cl-] | Concrete Strength [MPa] |
|-------|-----|-----------------------------------------------|-------------------------|-------------------------|
|       |     |                                               | 0-10 [mm]               | 10-20 [mm]              | 20-30 [mm] |                   |                       |
| 57-039-1 | 1   | 2nd abutment, left, wing wall                 | 0.04                    | 0.02                    | 0.01       | Suitable          | C16/20 20.4           |
| 57-039-2 | 2   | 2nd abutment, left, concrete patch            | 0.04                    | 0.03                    | 0.05       | Unsuitable        | C12/15 15.1           |
| 57-039-3 | 3   | 2nd abutment, right, wing wall                | 0.03                    | 0.03                    | 0.02       | Suitable          | C16/20 20.4           |
| 57-039-4 | 4   | 2nd abutment, right, concrete patch           | 0.22                    | 0.11                    | 0.08       | Suitable          | C12/15 15.1           |
| 57-039-5 | 5   | 1st abutment, middle bottom part              | 0.1                     | 0.06                    | 0.04       | Suitable          | C12/15 15.1           |
| 57-039-6 | 6   | 1st abutment, middle part under bearing seat  | 0.13                    | 0.18                    | 0.19       | Unsuitable        | C12/15 15.1           |
| 57-039-7 | 7   | 2nd abutment, middle bottom part              | 0.09                    | 0.09                    | 0.08       | Suitable          | C12/15 15.1           |
| 57-039-8 | 8   | 2nd abutment, middle bottom part              | 0.09                    | 0.22                    | 0.19       | Unsuitable        | C12/15 15.1           |
| 57-039-9 | 9   | 2nd abutment, middle part under bearing seat  | 0.26                    | 0.29                    | 0.3        | Unsuitable        | C12/15 15.1           |
| 57-039-10 | 10  | Girder no. 4, section 3                       | 0.03                    | 0.03                    | 0.03       | Suitable          | C40/50 53.9           |
| 57-039-11 | 11  | Girder no. 5, section 3, 2nd abutment         | 0.05                    | 0.04                    | 0.03       | Suitable          | C40/50 53.9           |
| 57-039-12 | 12  | Longitudinal joint between 3rd and 4th girder | 0.05                    | 0.03                    | 0.02       | Suitable          | C25/30 34.7           |
| 57-039-13 | 13  | Longitudinal joint between 4th and 5th girder | 0.04                    | 0.03                    | 0.03       | Unsuitable        | C25/30 34.7           |

| ID         | pH  | c(Cl-)/c(OH-) | Surface conc. [%Cl] | Diffusion coefficient [m.s⁻²] |
|------------|-----|---------------|---------------------|-------------------------------|
| 57-039-1   | 8.66| 8.06          | 126.27              | 105.89                        | 1.97E-13                        |
| 57-039-3   | 9.11| 8.58          | 110.68              | 1022.66                       | 1.63E-12                        |
| 57-039-4   | 8.48| 8.53          | 7.43                | 4269.5                        | 0.261E-13                       |
| 57-039-5   | 7.50| 7.30          | 7.86                | 750.44                        | 3.56E-13                        |
| 57-039-7   | 8.23| 8.01          | 7.14                | 540.44                        | 1.04E-12                        |
| 57-039-9   | 10.71| 11.60         | 11.89               | 1.42                          | 0.041E-11                       |
| 57-039-10  | 10.71| 11.60         | 11.89               | 1.42                          | 9.54E-13                        |
| 57-039-11  | 10.77| 11.75         | 11.84               | 1.11                          | 3.55E-13                        |
| 57-039-12  | 10.43| 9.78          | 11.34               | 2.16                          | 2.20E-12                        |