Uncertainty Quantification of Semi Destructive Testing for chloride content assessment for a concrete bridge in maritime environment

Franck Schoefs
Professor, Nantes Université, École Centrale Nantes, CNRS, GeM, UMR 6183, IUML, FR 3473, F-44000 Nantes, France

Keita Awa Zahui Raïssa
Graduate Student, Institut National Polytechnique Houphouët Boigny, Yamoussoukro, Côte d'Ivoire

Stephanie Bonnet
Professor, Nantes Université, École Centrale Nantes, CNRS, GeM, UMR 6183, IUML, FR 3473, F-44000 Nantes, France

Alan O'Connor
Department of Civil, Structural and Environmental Engineering, Trinity College Dublin, Ireland

ABSTRACT: Reinforced Concrete (RC) structures in harbors, are designed for a long time (50 to 70 years) and are unfortunately subjected to chloride-induced corrosion, a preponderant and very damaging pathology. Faced with this pathology Diagnosis of these structures usually relies on inspections which consist on ponding salt in the concrete cover with Semi-Destructive Testing (SDT). However, the Uncertainties in inspection result in bad diagnosis, and bad decisions. This paper aims at developing a methodology for quantification of uncertainty of measurements for on-site measurement where random properties of concrete plays a role. This assessment is performed through multiple measurements by 3 operators from 2 laboratories on the same cores extracted from a 27 years old existing bridge located in Ireland. A total of 566 measurements was available. The effect of the operator, the laboratory and the protocols are discussed and then modelled. It is shown that that the error of assessment is a function of the chlorides content and follows a student distribution. The standard deviation of this error reached around 15% of the chloride content. Then this error is propagated through the Fick law parameters for measuring its effect on the diagnosis: a 17% change of the probability of corrosion initiation is shown.

Keywords: Harbors, reinforced concrete, Chloride, semi-destructive testing, error of measurement, uncertainty, probability of corrosion.

1. INTRODUCTION

Harbors play a major socio-economic role in almost all littoral countries with more than 80% of trade exchange and play also usually a key role for military defense in Europe and all over the world. Reinforced Concrete (RC) structures in harbors are designed for a long time whereas marine environment is considered to be aggressive for RC structures. The main degradation mechanism is chloride-induced corrosion associated to different exposure conditions: tidal, splash and atmospheric whose boundaries have been defined by Bourreau (Bourreau et al., 2020).

To prevent any critical failure and optimize the maintenance, a diagnosis is usually made several times during the life-time. It usually relies on inspections which combine different techniques and among them Non-Destructive Techniques (NDT). A diagnosis in line with reality should be based on a clear understanding of the relationship between a measurement and a degradation level and the level of uncertainties. A concrete structure made with the same concrete presents variability especially when dealing with transfer properties such as chloride diffusion (Othmen et al., 2018). That leads to propose methods to investigate the spatial variability and thus to optimize the position of measurements. The diagnosis about chloride profiles relies usually on Semi-Destructive Testing (SDT) which goal is to pond salt in concrete: it is composed on several steps which includes the drilling of a core, its cutting up into lengths, crushing and finally carrying out a chemical test. Even if this assessment relies on a complex method, there is no commercial sensor with a proved implementation and efficiency on site and other methods such as resistivity showed also some limitations in terms of error and requires corrections of the measurements. SDT has been used in a large number of studies for materials tested in laboratories since the 90's. Tests on existing structures are rarer: Othmen et al. (2018) reviewed 10 published studies from 2004 to 2016 with only 3 concerning more than 30 measurements. However, none of them investigated the uncertainty of measurements. Papers dealing with epistemic uncertainties of chloride measurement did not consider uncertainty of assessment (Hamidane et al., 2020) or considered data for a model material created in the laboratory only (Hunkeler et al., 2000; Schoefs et al., 2022). Yet, this method requires high human means and its multiple steps lead to significant uncertainties even for a model material (Bonnet et al., 2020). Hinrichs (2012) reported that this standard deviation of the error of measurement could reach 0.01% chloride mass fraction referred to the mass of cement. Hunkeler et al. (2000) pointed out that the reproducibility standard deviation depends on the absolute amount of chlorides but no values is given for on-site assessment. Uncertainty in measurement can lead to bad decisions: the uncertainty of measurement is thus a key input in maintenance optimization to be quantified. Uncertainty of measurement in maritime conditions includes:

- Expertise, tiredness of the operator (Schoefs et al., 2012a);
- Protocol of on-site inspection (Schoefs et al., 2009);
- Processes of measurement in laboratories (Bonnet et al., 2020).

In Bonnet et al. (2020) and Hunkeler et al. (2000), the quantification of the error of measurement was performed on laboratory specimens made with normalized mortar submitted to a fixed well known quantity of chlorides. It is not directly transferable to concrete structures because the material is not the same; Moreover, the effect of chloride content on the error could not be investigated and there were no gradients of chlorides in depth for analyzing the effect on diffusion properties. That is the purpose of this paper in which it is aimed also to provide a quantification of uncertainty. In view to reach this objective, measurements taken on a littoral bridge in Ireland were used, on which concrete cores were extracted in order to conduct a study on chloride profiles (O'Connor and Kenshel, 2013): at total of 263 measurements of chlorides are available and allow performing a statistical analysis. The onsite cores are analyzed by 2 laboratories: one in Ireland and one in France. Moreover, two operators made the measurements in France. That allows to quantify the role of the operator and of the protocol. Moreover, the scatter in chloride content allows analyzing the dependence of the uncertainty to the level of contamination. Then the impact on the parameters of Fick law and on the diagnosis are analyzed.

Section 2 depicts the protocol, the location of measurements, and the transnational measurements. Section 3 presents the data and the quantity of interests: chloride content for decision at date of inspection and parameters of Fick equation calculated from these profiles. In section 4 the quantification and modelling of uncertainties are evaluated and modeled. Section 5 analyzes the effect of the error of measurement on the diagnosis of the bridge.

2. PRESENTATION OF THE STRUCTURE AND THE TRANSNATIONAL MEASUREMENTS

This section presents the Ferrycarrig Bridge, the structure from which concrete cores were extracted in order to conduct this study and the experimental program for obtaining these different measurements and the laboratories involved. Most of the information concerning the presentation of the bridge and the experimental program for obtaining the chloride profiles was collected in the PhD thesis of Dr. Omran Kenshel's (Kenshel, 2009).

After extraction of the cores, the experimental program started at the TCD laboratory with operations of cutting into 8 mm thick slices, crushing and grinding in order to reduce the different concrete cores into powder to extract the chloride according to the recommendation of the Eurocode (EN 14629). For the determination of the total chloride profiles in the different samples, a part of the powders of each sample is processed according to the recommendations of EN 14629 by an operator of the TCD laboratory (in Ireland) and another part by two operators (NU-P and NU-G) at the Nantes University laboratory (France) according to the acid soluble chloride method. Both protocols are chosen because they both follow RILEM recommendations (RILEM, 2002) and are representative of the most widely used methods for salt accumulation in concrete (Othmen et al., 2018).

3. DATA ANALYSIS

The available data were collected in 2007, after 27 years of exposure. From a semi-destructive assessment of chlorides from cores, two types of quantities of interest can be studied:

- The chloride content at a given position in the concrete cover, which is discussed in section 3.1
- The parameters of the model diffusion, from the profile analysis. The model and the data treatment are presented in section 3.2.

3.1. Chloride content

Following the experimental program of the different concrete beam samples, various chloride contents are obtained with chloride levels ranging from 0 to approximately 0.001478 g/g of concrete considering all cores and all operators. This level is quite low compared to that obtained on structures of the same age purely exposed at sea conditions (0.0025 according to Othmen et al., 2018), in the tidal zone. Moreover, during a more detailed analysis, it is noted that for the same position and core, the quantity measured varied according to the operators (Figure 1). This demonstrates the imperfect nature of chloride measurements in marine structures in RC. Therefore, a more careful analysis of the measurement discrepancies of the different operators is necessary. Protocols for obtaining chloride content being slightly different ad operators being different, a more detailed analysis is carried out. The objective is to investigate if these deviations are related to the quantity of chloride measured, to the protocol of assessment or to the operator.

Moreover, these measurements are generally used to determine the parameters of a model for the prediction of the chloride profiles with time, the objective being to evaluate the corrosion risk. An analysis of the impacts of the measurement differences on these parameters is carried out in sections 4 and 5.

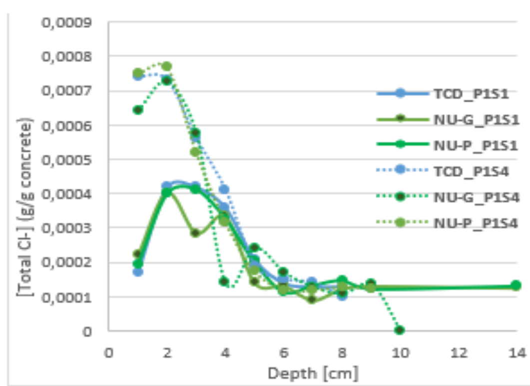

Figure 1: Example of total chloride profiles after 27 years of exposure showing the heterogeneity of measurements by different operators

3.2. Parameters of Fick model

After having determined the chloride content in the different cores, a treatment is carried out in order to determine the parameters of a prediction model.

The chloride profiles, with the exception of a few, shows a concentration gradient decreasing rapidly with the depth of the concrete. The model used for fitting the chloride profile (chloride content as a function of depth) is usually the Fick's model (Mejlbro, 1996). Unlike other models, it is highly preferred in the literature for the treatment of chloride profiles from RC structures in marine environments regardless of the exposure area for its simplicity and ability to be adapted to different exposure conditions (Othmen et al., 2018). Under the assumption of a homogeneous concrete, a constant surface content and a one-dimensional diffusion in a semi-finite space, the second law of the Fick's model used for the adjustment of the chloride profiles is expressed as follows:

$$C(x,t)=Ci+(Cs-Ci).erfc(x/(2\sqrt{Dt})) \qquad (1)$$

With C(x, t) the chloride content at a depth x (m) and after a time t (s); Ci (g /g concrete) the initial chloride content in the concrete before exposure; Cs (g /g concrete) the chloride content at the surface of the concrete and D (m^2/s) the apparent diffusion coefficient of the concrete. The fitting involving monotonic and strictly decreasing profiles, these have therefore been the subject of a pre-processing which is done in an individual way as recommended by (Othmen et al, 2018): all the data, from the surface to the point of maximum chloride content, are discarded. Selecting outliers is always a delicate task. Another data processing is used in this paper consisting in discarding each of the values considered as outliers in order to have profiles conforming to the expected pattern. Here data, deeper that the point of maximum chloride content, are discarded, after fitting, if they did not match the expected pattern: monotonous and strictly decreasing along the concrete depth. This may result from measurement errors, damage to the concrete (crack) or the quantity of available powder of concrete. After case-by-case studies 8 profiles are excluded.

Subsequently, the values of D, Ci and Cs are determined by iteration using the least square minimization criterion and the simplex optimization algorithm.

3.3. Chloride Method for quantifying error of measurement

The analysis of the various profiles of chlorides resulting from tests of repeatability carried out by the three operators (NU-P, NU-G and TCD) of the two different laboratories (NU and TCD) made it possible to highlight errors of measurement. In order to evaluate these errors, the data are subdivided into two series. The first series (series 1) concerned the data of the P1S beam, on which all three operators and the second series (series 2), made up of two operators from two different laboratories (NU-P and TCD), concerned the data from beams P1S, P2S, P2N, P3N, P3S, P4S, P4N(Table 1).

The actual amount of chlorides at each position is not known, so the nominal value is evaluated according to the procedure used by (Schoefs et al., 2009). This procedure consisted in considering this nominal value as being equal to the average of the measurements made by the different operators at the considered position. The assumption being this procedure is that operators or protocols are not at the origin of a systematic bias. Thus, measurement errors of each operator and this for each measurement are evaluated by making the difference between this average and the value measured by the operator considered and this for each series (Eq. 2).

$$\varepsilon_{j,i} = \hat{C}_{j,i} - \frac{\sum_{k=1}^{3} \hat{C}_{j,k}}{3} \qquad (2)$$

Where $\hat{C}_{j,i}$ is the chloride content measured by operator i at position j (beam, exposure, depth)

3.3.1. Error of each operator

From the analysis of the different chloride measurements, it is found that there is a heterogeneity between the values measured by the TCD laboratory and those of the Nantes

Université laboratory. Thus, the effect of the protocol and the devices of the laboratory is evaluated by statistical analysis. To do this, series 1 is considered. Indeed, although having less data (40), this series is the most adapted because it gathers the three operators (two from the laboratory of Nantes Université and one from TCD). Table 2 gathers all the estimates computed for this comparison: range, mean, standard deviation, maximum and minimum errors computed from Eq. (2).

Note that maximum/minimum errors are of the same order of magnitude as the threshold used to detect outliers in section 3.2, i.e. 10^{-3} (g Cl^-/g). It appears that there is no laboratory that provides an additional bias or standard deviation or a wider scatter compared to the other. Consequently, the measurements are not influenced by possible laboratory or type of protocols effect. Therefore, in the rest of the document, the work will only focus on the case where we have only the two operators: the series 2 for which 263 measurement are available.

Table 2: Statistical estimators of measurement errors: case of the series 1

ESTIMATORS	NU-P	NU-G	TCD
Range of measured chloride levels [g/g concrete]	[1.02; 7.66] 10^{-4}	[0.91; 7.26] 10^{-4}	[0; 7.40] 10^{-4}
Mean	-4.39 10^{-6}	8.12 10^{-78}	3.58 10^{-6}
Standard deviation	2.48 10^{-5}	3.90 10^{-5}	2.85 10^{-5}
Maximum error of overestimation	7.09 10^{-5}	7.08 10^{-5}	1.22 10^{-5}
Maximum error of underestimation	-7.17 10^{-5}	-1.48 10^{-4}	-5.64 10^{-5}
Bias	1.89 10^{-5}	2.55 10^{-5}	1.92 10^{-5}

As previously demonstrated, there is no laboratory effect on the orders of magnitude for the biases, standard deviations, ranges and maximum/minimum errors. Consequently, the global error statistics are determined by considering only the case of the two operators: series 2. The averages of the two operators C_{nom} are considered as the true values of the chloride content in the concrete, knowing now that there is no additional bias of one operator compared to the other (random hazard). Therefore, with two operators, for one measurement at position j (beam, exposure, depth) $\hat{C}_{j,i}$ of operator I, the error is computed according to Eq. (3)

$$\varepsilon_{j,i} = \hat{C}_{j,i} - \frac{\sum_{k=1}^{2} \hat{C}_{j,k}}{2} = \hat{C}_{j,i} - C_{nom} \qquad (3)$$

Error estimators are gathered in Table 3. Moreover, it appears that the two protocols lead to approximately the same standard deviation and bias. The global distribution of the error is therefore obtained by grouping the errors of the two operators (TCD and NU-P) and is the subject of a more detailed analysis in the following section. When comparing these errors to those published by Bonnet et al. (2020) on mortars in laboratory (standard deviation of 12 10-5 for an average chloride content of 2 10-3) the standard deviation is here of 6.7 10-5 for an average chloride content of 7 10-4. It is of same order of magnitude but 2 times lower. The reason is provided in section 4.1 where the link between chloride content and standard deviation of error is highlighted.

Table 3: Statistical estimators of measurement errors: case of the series 2

ESTIMATORS	NU-P	TCD
Range of measured chloride levels [g/g concrete]	[1.02; 14.39] 10^{-4}	[0; 14.78] 10^{-4}
Mean	-6.94 10^{-6}	6.94 10^{-6}
Standard deviation	6.66 10^{-5}	6.66 10^{-5}
Maximum error of overestimation	1.04 10^{-4}	5.49 10^{-4}
Maximum error of underestimation	-5.49 10^{-4}	-1.04 10^{-4}
Bias	3.20 10^{-5}	3.20 10^{-5}

MODELING

4.1. Uncertainty on chloride assessment

Focus is now placed on the distribution of the error and its modelling. The first question concerns the dependency of the error to the nominal level of chloride. This phenomenon is observed for the on-site resistivity assessment of coastal bridges (Bourreau et al., 2019) and for the assessment of Chloride Content for model materials (Hunkeler et al., 2000). The error is shown to increase slightly with the chloride content for chloride content below 0.0008 [g / g concrete]. For larger chloride contents, the nominal content is too low for expanding this analysis.

As a consequence, the standard deviation is modeled as an increasing function up to a nominal content of 0.008 [g / g concrete] and considered as constant for higher values. To this end and in view to compute accurately the standard deviation, the set of measurements is divided into 6 intervals with 46 values for each one: that allows a good statistical estimate of the standard deviation. For each of the 6 intervals, mean of chloride content and standard deviation of errors are computed. Figure 2 plots the evolution of the standard deviation with nominal content up to 0.008 [g / g concrete]. It shows a clear quadratic shape which equation is given in Eq. (4) and. Eq. (5) gives the value to be used for higher chloride contents. The range of standard deviations [1.10-5; 1.2.10-4] kg Cl-/kg concrete is lower than the one obtained by Hunkeler et al. (2000) ranging between 0.00008 to 0.00010 (kg/kg cement) i.e. between [1.610-5; 2.10-5] (kg/kg cement) for a concrete density of 2320 kg/m3 and cement content of 375 kg/m3) (Kenshel, 2009, p. 45). However, tests of Hunkeler et al. are carried out on materials casted in laboratory.

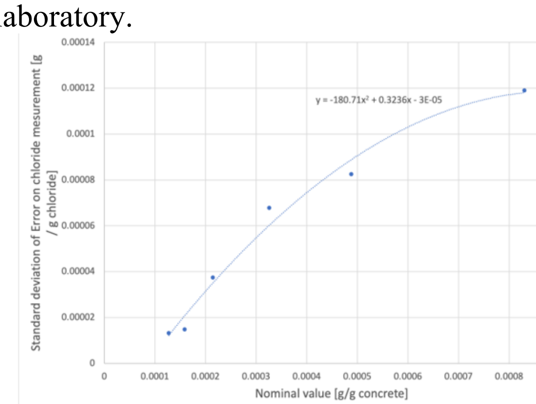

Figure 2: Evolution of the standard deviation of the error of measurement as a function of the reference.

$$\sigma_\varepsilon = 80.71\, C_{nom}^2 + 0.3236\, C_{nom} - 3.10^{-05} \quad (4)$$

for $C_{nom} \leq 0.008$ [g / g concrete]

$$\sigma_\varepsilon = 1.2\ .10^{-04} \quad (5)$$

for $C_{nom} > 0.008$ [g / g concrete]

where σ_ε denotes the standard deviation and Cnom the nominal value.

In view to propagate the corresponding uncertainty through degradation (Diffusion for instance) models in a Risk Based Inspection framework, let us now focus on the probabilistic modelling of the distribution of the error. A normal probability density function (pdf) is usually suggested but it is shown that this assumption should be tested before its selection (Schoefs et al., 2009). Figure 3 plots the pdf and the experimental distribution. Both the Figure and the statistical estimate (MLE) show that the t-location scale pdf is the best candidate. Note that it is also selected for the error of measurement of marine corrosion (Schoefs et al., 2009).

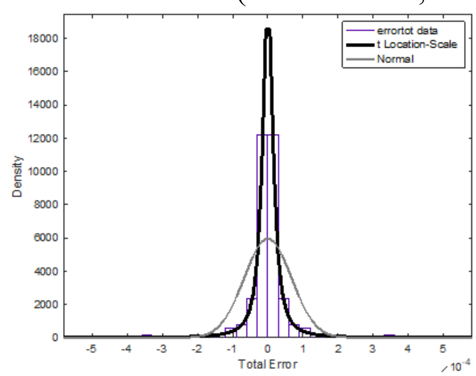

Figure 3: Normal and t-location scale pdf used for fitting the distribution of errors.

The error is zero-mean with a standard deviation following Eq (4) and Eq (5). These two parameters and knowing that the degree of freedom is ν = 1.36097 (Table 4), the distribution of errors is conditioned by the predicted nominal value and follows t-location scale pdf. This modeling allows computing the error of assessment of chloride content from SDT and the Probability of Detection and Probability of False Alarm. These inputs are required in RBI (Risk Based Inspection) frameworks for analyzing their effect on the OPEX (OPerational EXpenditure) or the MOI (Multi-Objective Index).

4.2. Uncertainty on Fick law parameters

Error of measurement affects the chloride profiles. As a consequence, parameters of Fick law are also affected and the error will propagate with time when using this equation for chloride prediction. The aim of this section is to analyze this error by treating the profiles obtained for each operator of series 2.

Note that profiles are first built by using a nominal profile built with the mean value of each operator (Cnom in (3)). Then the parameters of the fitted Fick law are calculated and compared. In order to evaluate the impact of measurement uncertainties on the Fick's parameters, D, Cs and Ci, statistic properties are compared. The set (mean (μ); standard deviation (σ); coefficient of variation (CoV) and distribution law) obtained by TCD and NU-P are compared to the values obtained with the nominal profile: μnom, σnom, CoVnom. First of all, regarding the pdf and according to the MLE, it is found that those of the parameters D and Cs follow a Log-Normal distribution law, which is a consensual selection in the literature (Othmen et al., 2018; Clerc et al., 2019). It appears that the pdf of these parameters is not influenced by the measurement errors, and is therefore independent of the operator. In addition, parameter Ci follows a rather asymmetrical distribution. However, Ci being distributed on extremely low orders of magnitude, a good estimate of the distribution law is not reachable: the scatter of the distributed values distribution has the same order of magnitude than the accuracy of measurement devices i.e. the standard deviation computed previously. Table 5 gathers the statistical estimates of the nominal profile for D, Cs and Ci. Average values of diffusion coefficient and chloride content at the surface are respectively 0.686 10-12 m2/s and 0.0063 kg Cl-/kg concrete: these values are consistent with those obtained in similar structures, reviewed by Othmen at al. (2018) and ranged in the intervals [0.27 10-12; 5.13 10-12] and [0.003; 0.013] respectively for D and Cs.Note that the chloride measurement error is reversed when looking to TCD, in comparison with NU-P because the mean value of measurements from two operators is assumed to be the true value. This table also shows a significant coefficient of variation for Ci and Ds (around 50%) and a high coefficient of variation for Cs (around 80%) which are consistent with the literature (Othmen et al., 2018). The relative difference between TCD and NU-P values in comparison with the nominal values are also reported in Table 5. They are computed according to (6).

$$\%X = \frac{X - X_{nom}}{X_{nom}} \qquad (6)$$

Where X is μ, σ or CoV.

Table 5 : Statistics of the D, Ci and Cs of the two operators compared to those obtained by considering the average chloride (nominal value).

Operator	Parameters of the nominal profile		TCD		NU-P	
Chloride measurement error (Eq. 3)			[-1.04 10^{-4}; 5.49 10^{-4}]		[-5.49$10^{-4}$; 1.04 10^{-4}]	
Parameters	(μ_{nom} ;σ_{nom})	CoV_{nom}	(%μ ;%σ)	%CoV	(%μ ;%σ)	%CoV
Ci (% Cl^- / mass of concrete)	(0.011 ; 0,006]	0,52	(-8% ; -71%)	-56%	(-10% ; -35%)	-22%
Cs (% Cl^- / mass of concrete)	(0.163 ; 0,129)	0,79	(21% ; 47%)	33%	(-17% ; -4%)	12%
D (10^{-12} m^2/s)	(0.686 ; 0,363)	0,53	(0.001% ; -9%)	-9%	(0.4% ; -19 %)	-19 %

These results highlight the sensitivity of the error to the operator and that repetitively tests are needed for provided an average value that could be used as a decision support. This issue is investigated in the next section.

5. CONCLUSIONS

Today, most diagnostics of reinforced concrete structures in the marine environment are based on semi-destructive testing for the presence of salt in concrete cores. This multi-step process is complex and the measurements are uncertain. Depending on the level of uncertainty, decisions based on the diagnosis can be affected: unnecessary repair or failure due to a missed repair. This paper investigated the level of uncertainty for chloride profiles during on-site measurements by different operators from 2 laboratories and its effect on the diagnosis. The main conclusions are: - It is shown that the two protocols used by the operators in two laboratories do not lead to systematic bias i.e. over/underestimation of chloride content.

- The error of measurement depends highly on the chloride content: the more the chloride content, the more the error until it reaches an asymptotic value.
- An analytical model of the standard deviation was provided.
- The error was shown to follow a t-location scale pdf whose parameters are provided as functions of the chloride nominal value.
- It was shown that the initial concentration Ci was highly affected by the use of a single operators, mainly because the initial chloride content is close to the accuracy of assessment.
- It is recommended to use repetitively tests with two operators to get the surface concentration of chloride which is a key parameter for chloride content prediction.

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