

## In situ DC electrical resistivity mapping performed in a reinforced concrete wharf using embedded sensors

Johann Priou, Yann Lecieux, Mathilde Chevreuil, Virginie Gaillard, Cyril Lupi, Dominique Leduc, Emmanuel Rozière, Romain Guyard, Franck Schoefs

## ▶ To cite this version:

Johann Priou, Yann Lecieux, Mathilde Chevreuil, Virginie Gaillard, Cyril Lupi, et al.. In situ DC electrical resistivity mapping performed in a reinforced concrete wharf using embedded sensors. Construction and Building Materials, 2019, 211, pp.244 - 260. 10.1016/j.conbuildmat.2019.03.152 . hal-03484514

## HAL Id: hal-03484514 https://hal.science/hal-03484514

Submitted on 20 Dec 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers. L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

# In situ DC electrical resistivity mapping performed in a reinforced concrete wharf using embedded sensors.

3	Johann Priou <sup>a</sup> and Yann Lecieux <sup>a*</sup> and Mathilde Chevreuil <sup>a</sup> and Virginie Gaillard <sup>b</sup> and Cyril
4	Lupi <sup>a</sup> and Dominique Leduc <sup>a</sup> and Emmanuel Rozière <sup>c</sup> and Romain Guyard <sup>a</sup> and Franck
5	Schoefs <sup>a</sup>
6	<sup>a</sup> Laboratoire GeM (UMR 6183), Université de Nantes, CNRS, Centrale Nantes, 2, rue de la
7	Houssinière, 44322 Nantes Cedex 3, France
8	<sup>b</sup> Laboratoire GeM (UMR 6183), ICAM, Département Génie Electrique, 35 Avenue du champ
9	de Manœuvres, 44470 Carquefou, France
10	<sup>c</sup> Laboratoire GeM (UMR 6183), Centrale Nantes, CNRS, Université de Nantes, 1 Rue de la
11	Noë, 44321 Nantes Cedex 3, France*

#### 12 Abstract

Installation, calibration protocol and data analysis of multi-electrode sensors embedded in 13 concrete are proposed in this study. Measurements of resistivity are performed in a port wharf and 14 analyzed in parallel with measurements of humidity, temperature, and evolution of the mechani-15 cal strength of concrete. The correlation between the evolution of the compressive strength and 16 the resistivity, allows to validate the measurement protocol proposed. To visualize the distribu-17 tion of resistivities in the studied volume, pseudo-sections of apparent resistivity were displayed. 18 A methodology to plot and use them as an indicator of corrosion adapted to civil engineering 19 structures is proposed. 20 Keywords: Electrical DC resistivity, SHM, Embedded sensors, Coastal structures, Concrete 21

#### 22 1. Introduction

The electrical resistivity quantifies the ability of a material to oppose the flow of electric current. This physical characteristic is related to the nature of the medium, its porosity and its electrolyte content. Direct Current (DC) electrical resistivity measurements have thus naturally been used for many years in geophysics to obtain subsoil images by tomography [1, 2] and estimate its constitution (type of rock, presence of water, trace of pollutant, etc.). In rocks the electric

March 1, 2019

<sup>\*</sup>Corresponding author. Email: yann.lecieux@univ-nantes.fr Preprint submitted to Elsevier

current propagates essentially through the open porosity by the intermediate of the interstitial flu-28 ids, generally water [3]. The electrolytic resistivity of rock is given by Archie's empirical law 29 [4, 5]. The conduction via the pore solution of concrete can also be described by the Archie's law 30 [6, 7]. Resistivity measurements are therefore also used in civil engineering for various appli-31 cations. These include crack detection [8], porosity or mechanical strength monitoring [9], and 32 concrete moisture content assessment [10, 11, 12]. Corrosion monitoring, the issue of interest in 33 this study, is also an important field of application for resistivity measurement [13, 14, 15, 16]. 34 The resistivity value is used as an indicator of the probability of corrosion. In the case of pit-35 ting corrosion induced by chlorides, it is possible, by calibrating the resistivity measurement, to 36 assess the level of free chloride in a given concrete [10, 17, 18, 19, 20]. 37

One hundred works and applications covering the field of resistivity measurement in concrete were identified in the reviews [21, 22]. Most of the experiments listed in [21] were carried out in the laboratory on test specimens without reinforcement bars.

Many measurement devices exist such as: discs, devices with 4 electrodes arranged in squares 41 or aligned and most often interrogated with a Wenner protocol. There are also multi-electrode 42 devices that allow, as in Geophysics, to display a resistivity section of the medium [23, 18, 24]. 43 For on-site applications the most commonly used devices are portable Wenner probes for punc-44 tual measurement. Although simple to use and relatively inexpensive, they have two significant 45 drawbacks. On the one hand, this system is suitable for punctual measurements as part of inspec-46 tion campaigns. It is not designed to be integrated into a SHM (Structural Health Monitoring) 47 measurement chain. On the other hand, the repeatability and reproducibility performances of 48 these probes are lower than those observed with embedded devices. Coefficients of variations 49 between 10% and 25% have been reported for variability measurements performed in specimens 50 of the same batches and exposed identically [13, 25, 26, 18]. This dispersion has several origins, 51 including the variability of the material and the variability of the contact resistance between the 52 concrete surface and the measuring electrodes [27]. This observation shows the importance of 53 the quality to bring to the electrical contact to ensure the reproducibility of the measurement. For 54 this purpose it is more interesting to opt for an embedded sensor in order to improve the perfor-55 mances of the measuring system. It also offer the possibility to perform several measurements 56 in the same location to avoid any bias due to material spatial variability of physical properties of 57 concrete. This local variability is shown to have significant influence on resistivity measurement 58

<sup>59</sup> due to the change of the path of current lines [27]. Spatial variability of chloride content [28] is
<sup>60</sup> also an issue.

To take full advantage of all the possibilities offered by electrical DC resistivity measurement [21, 22], current works must now focus on *in situ* installation of devices integrated into SHM measurement chain. These sensors should have the following characteristics:

- be embedded in concrete during the construction of the structure, to improve the repeatability of measurements, to get data in areas that are difficult to access and to follow the evolution from concreting to operation time;
- take into account the presence of reinforcement bars, either through a correction of the
   measurement [13, 29], or through a specific installation protocol [30];
- take temperature variations into account [31, 32, 24];
- give a large number of measurement points to decrease the amount of false alarm or bad detections [24, 33, 23, 18];
- obtain a mapping of resistivity in the concrete cover area [33, 23, 18] and better asses
   spatial variability.

The objective of this study is to propose a complete methodology for the installation and use of an on-site resistivity measurement device for the continuous monitoring of a reinforced concrete structure located in the splash zone of a marine environment, from its construction to its dismantling. The methodology addresses the following points:

- the *in situ* installation;
- the calibration protocol;
- the data analysis.

The section 2 is dedicated to the presentation of the sensors and their installation in a port wharf located at the mouth of the Loire river (on the west coast of France). Resistivity sensors (based on the technology used in the study [18]) were installed on two beams during the construction of the wharf together with temperature and humidity sensors. The sensors were installed within the framework of the project iMARECO2 (french acronym for Monitoring for

Maintenance, Reassessment and Optimal Design) managed by Keops Automation, with partners 86 Université de Nantes, Nantes - Saint Nazaire Port and Bouygues Construction. It relies on the 87 monitoring of a wharf during its construction, commissioned by Nantes - Saint Nazaire Port 88 (Nantes - Saint Nazaire harbor, France). This section also describes concrete characterizations 89 performed in laboratory. The principle of resistivity measurements with our sensors and their 90 experimental validation are presented in section 3. The section 4 is the core of the analysis. It 91 presents original developments on the adaptation of conventional methods used on geophysics 92 to civil engineering structures, which allow the display and exploitation of apparent resistivity 93 measurements. The last section, "results and discussion", is dedicated to the presentation of all 94 the measurements (resistivity, humidity, temperature, compressive strength) and the correlations 95 between the different measurements. The evolution of concrete at early age and then during the 96 first year of the structure is monitored. The observation of phenomena related to concrete setting 97 made it possible to validate measurement protocols and analysis methods, as well as to assess 98 the *in situ* performances of the resistivity sensor and the measurement method proposed. 99

#### **2. Material and Methods**

## 101 2.1. Studied structure and measurement system

#### 102 2.1.1. The wharf

The instrumented structure is a 350 meter long, 50 meter wide on pile wharf with a platform 103 (slab and beams) in concrete. The structure is made of partly precast reinforced concrete elements 104 (see Figure 1a). Precast elements are supported by 579 steel piles distributed over 10 longitudinal 105 rows and 56 transverse rows (see Figure 1b). The precast elements are first laid down on the heads 106 of steel piles. The junctions between these elements are reinforced with steel bars and then filled 107 with concrete for ensuring the embedded connection. The concrete elements act as formwork for 108 the structural parts of the wharf called "beams". Two beams at the end of the wharf are equipped 109 with sensors. They are marked in Figure 1b. 110

#### 111 2.1.2. Structural Health Monitoring (SHM) system for resistivity measurement

The wharf has been equipped with a multi-sensor system for the monitoring of concrete ageing. The measurement chain is designed to detect the long term penetration of chloride ions before it reaches the reinforcement and pitting corrosion begins. We are therefore particularly interested in the monitoring of concrete cover (see Figure 2a). The studied concrete elements are



Figure 1: The wharf: building system and sensors location.

in the splash zone. Humidity, temperature and resistivity sensors were embedded in the concrete

during the construction of the structure. They are located in each beams as shown in Figure 2.



Figure 2: Location of resistivity sensors (referenced RS).

<sup>118</sup> The lower part of each instrumented beam is equipped with:

• 2 resistivity sensors designed on the technology described in section 2.2;

- 3 combined humidity and temperature probes (ROTRONIC);
- 2 temperature probes Pt100.

Pt100 temperature sensors and humidity probes are positioned near resistivity sensors. Tem-

perature sensors are used for the compensation of thermal effects on resistivity measurements.

They have also been used to determine the mechanical strength of *in situ* concrete using the maturity method. Position of these sensors are presented in Figure 3.



Figure 3: Schematic view of the longitudinal cross section of the beam: location of temperature and humidity sensors. The label i = 1 or 2 is the beam number.

Data acquisition for temperature and humidity sensors is carried out with a NI cDAQ-9133 acquisition unit. The whole installation (batteries, electronics, central unit, wires for resistivity measurement) allowing data acquisition has been integrated into waterproof boxes to protect it from external aggressions (wind, rain, tide, etc.). The boxes are positioned at the downstream end of the platform as shown in Figure 1.

#### 131 2.2. The resistivity sensor and its acquisition device

The sensor embedded in the concrete structure consists of 32 electrodes in stainless steel spaced of a = 35 mm screwed into a 1.135 m long PVC bar. The exact dimensions of the sensors are visible in the Figure 4.

The resistivity measurements are performed punctually with a resistivimeter ABEM terrameter LS used by geophysicists which can also be used for civil engineering applications [18, 23]. The device injects current and measures potential differences on a line containing 4 to 32 electrodes in a user-defined sequence. Parameters such as the intensity of the current injected and the injection time are adjustable. The optimization of these parameters has been the subject of preliminary studies [18].

141 2.3. Proposed in situ installation of the resistivity sensor

The sensor installation has to meet the following operational constraints:



Figure 4: Sketch of the 32 electrode sensor. Dimensions are given in millimeters.

• First, the sensors must be placed in the center of the beams. This location required an opening on two prefabricated elements positioned side by side (see Figure 5a and 5b). The state of the structure before installation of the sensors is thus described in these figures 5a and 5b. The opening must then be filled with concrete poured into a formwork added to the structure after installation of the sensors (area drawn in red in Figure 5c);

- No electrical wires should run from the concrete bottom surface to the reinforcement to avoid creating a preferential path for seawater;
- The installation must be fast so as not to slow down the construction process;
- The sensor must probe the most relevant area. The concentration of chlorides is the highest
   in the zone located between 0 and 5 centimeters under the external concrete surface [10].
   Cover concrete is then the zone where monitoring is the most interesting for early detection
   of chloride ion penetration in concrete and therefore detection of corrosion risk;
- The sensor must be insensitive to reinforcement bars. Indeed, the data analysis is based on a finite element (FE) simulation. If the sensor were sensitive to reinforcement bars, it would be necessary to accurately modelized these bars in order to take into account their

influences on the resistivity measurement. However, on site, the actual positioning of the
 reinforcement bars is never exactly the same as planed. It would therefore be necessary
 to perform an accurate position report of the actual reinforcement bars. Moreover, as the
 reinforcement bars used are different according to the location within the beam, it would
 be necessary to carry out a different FE model of the volume studied for each sensor.
 Last, FE models representing reinforcements are complex and cannot be simplified. The
 simulations would therefore be expensive in terms of calculation time.



Figure 5: View of precasted concrete elements before (a and b) and after (c and d) the sensors are installed.

The technical solution chosen for the installation of the sensors, in agreement with all the criteria listed above, consists in installing the two sensors on a welded wire mesh of the size of the opening in the concrete (see Figure 5c). It was fixed on the 16 mm diameter reinforcements visible on Figure 5d. The wire mesh is connected to the ground of the measuring instrument via
 an electrical wire.

A welded wire mesh with a sufficiently fine mesh can be considered as a conductive plate. 170 Adding a conductive element between the reinforcement and the sensors confines the electrical 171 currents within the volume delimited by the concrete surface on the bottom side and the welded 172 mesh on the top side. The interest of the system is twofold. First, the resistivity measurement is 173 thus rendered insensitive to the presence of conductive elements (the reinforcement) located on 174 the other side of the conductive plate. Secondly, the volume surveyed using resistivy measure-175 ments is simple to modelize, since it is a rectangular volume without reinforcements except the 176 welded mesh (see volume in red in Figure 5c). 177

On site, however, it is not possible to install a metal plate or very dense mesh. The meshes must be wide enough to allow the aggregates and the needle to vibrate the concrete to pass through. A 35 mm mesh could be installed on site. A numerical sensitivity analysis performed with a model of the welded mesh and presented in the section 4 demonstrates that the mesh size used here is acceptable to avoid that the reinforcement bars influence the measurements of resistivity in cover concrete.

#### 184 2.4. Materials and mixture used on-site

The composition of cast-in-place concrete is given in Table 1. The strength class was C40/50
and the mixture complied with the requirements of French Standard NF EN 206-1 for XA2
exposure class; i.e. minimum binder content of 350 kg/m<sup>3</sup> and maximum Effective water to
Binder (Weff/Beq) ratio of 0.50. Portland cement CEM I 52.5 N SR3 was used to provide sulfate resistance. The actual Weff/Beq ratio was 0.45.

	Content (kg/m <sup>3</sup> )
Gravel 11/22	740
Gravel 2/10	300
Sand 0/4	810
Cement CEM I 52.5 N SR3 (C)	360
Plasticizer	3.8
Water effective	161

Table 1: Composition of concrete mix

#### <sup>190</sup> 2.5. Characterization of concrete performed in laboratory environment

In addition to the measurements carried out on site, laboratory tests were performed in order to get key properties of the concrete. The day when the beams were casted, 40 cylindrical samples of 110 mm diameter and 220 mm height were made with the same concrete and at the same time. After one day, they were stored in water at 3 different temperatures, 10 °C, 20 °C and 40 °C. The aim of the characterization tests was to obtain:

• the porosity accessible to water;

• the compressive strength;

• the equivalent age.

Permeability is an indicator of concrete durability since it controls the rate at which aggres-199 sive agents such as ions in sea water can penetrate into concrete. Number of scientific studies 200 underline the strong correlation between the porosity of a concrete and its permeability [34, 35]. 201 When porosity is reduced, permeability also decreases. Porosity is thus an essential character-202 istic of reinforced concrete [36]. In this study, water porosity was assessed after 90-day wet 203 curing on three concrete discs by the vacuum water saturation method, according to French stan-204 dard NF P18-459. An interesting feature of the resistivity comes from its link to porosity since 205 porosity evolves with hydration [37]. Porosity decreases during the first 90 days leading to an 206 increase in resistivity. At the same time, the mechanical strength of concrete is influenced by 207 porosity. Resistivity measurement can thus be considered as an interesting indicator of durability 208 [38] and material hardening. Thus, in section 5, resistivity measurements are compared with 209 porosity measurements. Then, the evolution of the *in situ* mechanical strength is computed at an 210 equivalent age. 211

Compressive strength characterization was also carried out in laboratory. The compressive 212 strength was measured at 1, 2, 7 and 28 days on the specimens stored in water at  $10^{\circ}$ C,  $20^{\circ}$ C and 213 40 °C. 30 specimens were tested, i.e. 3 specimens on day 1 and 3 specimens for each temperature 214 range on days 2, 7 and 28. The objective of these tests was to assess the compressive strength 215 of the concrete of the *in situ* structure. For this purpose, the maturometry technique was used. It 216 aims at the computation of the age of an on-site concrete equivalent to a concrete stored in the 217 laboratory at a reference temperature  $T_{ref} = 20$  °C. This calculation requires knowledge of the 218 thermal history of the structure (measured with PT100 probes) [39, 40]. Maturometry is firstly 219

based on the fact that the compressive strength of concrete depends only on its temperature. For
a constant temperature, the mechanical strength of concrete can be described by the following
expression [41]:

$$f_c(\tau; T, T_{\rm ref}) = f_{c_{28d}}(T_{\rm ref}) e^{s(T_{\rm ref}) \left(1 - \sqrt{\frac{28}{\tau(t; T, T_{\rm ref})}}\right)}$$
(1)

where  $\tau$  is the age of the concrete in days for the reference temperature  $T_{ref}$  or the equivalent age for a temperature  $T \neq T_{ref}$ , *s* the adjustable parameter and  $f_{c28d}$  the compressive strength assessed at 28 days and at the reference temperature, here chosen  $T_{ref} = 20$  °C.

Secondly, the sensitivity of concrete hardening to temperature is given by Arrhenius law, whose unique parameter  $E_a$  called apparent activation energy [J/mol] characterizes the curing of a concrete. The activation energy is related to the equivalent age of the concrete and its thermal history by the following relationship (2) [42]:

$$\tau(t;T,T_{\rm ref}) = \int_0^t e^{-\frac{E_a}{R} \left[\frac{1}{T(\theta)} - \frac{1}{T_{\rm ref}}\right]} d\theta$$
(2)

where *t* is the considered time period (days), *R* is the gas constant 8.314 J/mol.K and *T* (K) is the average absolute temperature of concrete.

It is thus possible to calculate the apparent activation energy of a concrete from the mechanical strength of the material stored at different temperatures following these steps:

- First, parameter *s* in equation (1) is determined from the mechanical strength curve of the samples stored at  $T_{ref} = 20$  °C;
- In a second step, the parameter  $E_a$  is calculated in such a way as to minimize the difference between the compressive strength measurement at 10 °C and 40 °C considering equivalent age computed with equation (2) and the model of the equation (1);
- Once  $E_a$  has been determined, the equivalent age of the actual structure can be determined at any point on the structure equipped with a temperature probe;
- Then, it is possible to calculate the mechanical strength of the real concrete at a given time
   with equation (2) using experimental data collected in laboratory and on-site temperature
   measurement.

# Resistivity measurement: protocol and performance assessment within the framework of the *in situ* installation

#### 246 3.1. Principle and protocol

The resistivity measurement technique used in this study is the direct current electrical tomography method. It is commonly used in the field of geophysics [1]. This measurement technique consists in successively using several sets of four surface electrodes to obtain one resistivity measurement. Two electrodes are used to inject an electric current into the studied volume. These two electrodes are respectively labelled A (injected current I) and B (injected current -I) (see Figure 6). The other two electrodes labelled M and N are used to measure a potential difference  $\Delta V$ .



Figure 6: Principle of the resistivity measurement with a four electrode device. The equipotential surfaces drawn on the Figure correspond to a semi-infinite homogeneous medium.

For a homogeneous medium of resistivity  $\rho$  ( $\Omega$ m), the relationship between the imposed current I, the potential difference  $\Delta V$  and the resistivity is given by equation (3):

$$\rho_{app} = G \frac{\Delta V}{I} \tag{3}$$

where G (1/m) is the geometric factor. This geometric factor is only function of the interrogation protocol (Wenner alpha, beta, gamma, Schlumberger, Dipole-Dipole) and of the geometry of the studied volume. In geophysics, the medium is assumed to be semi infinite. In this case, Gdepends only on the distance between the electrodes of the considered quadripole. For a Wenner alpha protocol, AM = MN = NB = a, thus  $G = 2\pi a$ . The factor  $2\pi a$  is also the one used for the analysis of potential measurement performed with a portable resistivity probe. However, if the medium is not semi-infinite, (for instance in in civil engineering in beams or slabs), G depends also on the specimen geometry. In such a case, the G factor has to be evaluated numerically or experimentally.

Finally, when the medium is not homogeneous, the resistivity, calculated from equation (3) is called apparent resistivity. The 32 electrodes of the sensor allow m = 129 measurements with the Wenner alpha protocol. The corresponding sequence is given on Figure 7.



Figure 7: Graphical representation of the Wenner alpha protocol measurement points with respect to the positions of the 32 electrodes.

267

From the *m* experimental or numerical measurements we deduce the geometric factors  $G^{j} = \rho \frac{I}{\Delta V^{j}}$ , for j = 1, ..., m. These are used to define the measured apparent resistivities  $\rho_{app}^{j} = G^{j} \frac{\Delta V^{j}}{I}$ linked to the *j*<sup>th</sup> measurement.

Resistivity measurements were performed during 18 months, several times a week during the first weeks in order to observe the evolution of concrete at early age. Further measurements are planned during next years but on a half-yearly basis. From all these measurements a resistivity mapping is obtained. It represents the apparent resistivity of the volume located under the measuring electrodes and it is called pseudo-section of apparent resistivity.

276 3.2. Assessment of measurement repeatability and trueness in laboratory and in situ

The quantification of measurement uncertainties is necessary, especially in civil engineering since concrete is a heterogeneous medium. Thus, the repeatability of the resistivity measurements was evaluated on site within concrete and in a homogeneous environment of constant

resistivity but including the same welded mesh as for the on-site installation. A model of the 280 volume of concrete studied on site was reproduced for laboratory tests (volume in red in Figure 281 5c). A wooden mould was equipped with a welded mesh and a resistivity sensor identical to 282 those embedded on site in the concrete beams. The volume was filled with water maintained at a 283 constant temperature of 20° C. The resistivity of water was obtained using a conductivity probe 284 considered as the reference. Five repeatability tests have been performed for each of the m = 129285 measurement points  $\{M^j\}_{j=1}^m$  (Figure 7). The repeatability error is computed as the coefficient of 286 variation of the sample  $\tilde{\rho}^{j} = \{\rho_{app,k}(M^{j})\}_{k=1}^{5}$  containing the 5 values of the repeatability test: 287

$$\operatorname{CoV}(\widetilde{\rho}^{j}) = \frac{\sqrt{\operatorname{Var}(\widetilde{\rho}^{j})}}{\overline{\rho}^{j}}, \ j \in \{1, \dots, m\}$$
(4)

where  $\bar{\rho}^{j}$  and  $\operatorname{Var}(\bar{\rho}^{j})$  are the mean value and the variance of the sample  $\bar{\rho}^{j}$ . Repeatability tests were performed in water of variable resistivity. The resistivity values [23, 92  $\Omega$ m] are chosen to match with the values expected to be measured on site. The value of about 20  $\Omega$ m is expected for a concrete at early age while 100  $\Omega$ m could be the resistivity value of a concrete with a high water saturation after few weeks. The results are plotted on Figure 8 with respect to the sequence of measurement points presented in Figure 7.



Figure 8: Coefficients of variation  $CoV(\rho^j)$  of the m = 129 measurements for tests performed in water using 10 mA current injection.

<sup>294</sup> The coefficients of variation are very low in both cases since they are less than 0.55 % (except <sup>295</sup> the value of 0.87 for one measurement) and close to those found in [25]. It should be noted that <sup>296</sup> after one year, the average value of the resistivity measured on site was less than 100  $\Omega$ m and <sup>297</sup> consequently, the input parameters of the device (injected current, time of injection, protocol,etc.) <sup>298</sup> are adapted. Similarly, repeatability tests conducted on the wharf made it possible to evaluate the <sup>299</sup> performance of the *in situ* device as shown in Figure 9.



Figure 9: Coefficient of variation  $\text{CoV}(\tilde{\rho}^j)$  of the m = 129 measurements for tests performed *in situ* using 10 mA current injection.

The value of the coefficient of variation recorded on site is slightly higher than that observed in the laboratory, but remains very low (less than 0.6 %). The difference is explained by the presence of more sources of uncertainties *in situ*, including variations in contact resistance or poor compensation for thermal effects. It is also possible to assess the accuracy error but only for measurement performed in water and using the geometric factor computed numerically. For a set of 5 repeatability tests, a reference value is given by the conductivity probe  $\hat{\rho}$ . The bias is computed using the equation (5):

$$b^{j} = |\hat{\rho} - \bar{\rho}^{j}|. \tag{5}$$

The bias also represents the trueness error in this case. It represents in particular the error on 307 the modelling performed using the direct finite element model since the bias is related to an 308 approximate numerical evaluation of the geometric coefficient G. The results obtained confirm 309 the global relevance of our finite element model (see section 4) since the relative bias is low (in 310 average 0.7  $\Omega$ m for the medium of 23  $\Omega$ m and 2.4  $\Omega$ m for the medium of 92  $\Omega$ m) except for 12 311 measurement points (see Figure 10). The latter are those made with the electrodes at the ends of 312 the sensor. This means that FE modelling does not correctly predict the propagation of current 313 near the lateral edges of the sensor with this geometric configuration. Consequently, in the rest 314 of the study, in order to avoid misinterpretations this measures were removed from the database. 315 Finally 117 measurement will be kept (129 minus 12 measurements, *i.e.* two measurements at 316 each end of the sensor for a given spacing, considering 6 different spacings). 317



Figure 10: Relative bias  $b^{j}$  of the m = 129 measured apparent resistivities for tests performed in water using 10 mA current injection.

#### 318 4. Mapping of resistivity measurements

The set of m=117 resistivity measurements obtained for a given time period allow three levels of analysis to be performed:

- The average apparent resistivity representative of the material is estimated from a large number of measurements performed in a small volume. The dispersion of the measurements reflects the heterogeneity of the concrete. The average value is useful information for the monitoring of hardening concrete (see section 5). By testing a material containing a given chloride content [20, 18] it is also possible to estimate a probability of detection of an average free chloride content in the survey area by knowing both average apparent resistivity value and dispersion of the measurements;
- The measurements can be displayed directly through a pseudo section of apparent resistivity. It does not require numerical inversion and thus allows an instant display of the measurement results. It is then possible to visualize areas for which the resistivity varies between two measurement campaigns as well as gradient effects due to chloride and humidity. Apparent resistivity is also useful for calculating the true resistivity obtained by reverse analysis. Indeed, in all algorithms currently in use, the initial value of true resistivity is the apparent resistivity.
- The true resistivity obtained by inversion allows the exact location of areas of variable resistivity. However, there is currently no algorithm available to quickly and reliably reverse apparent resistivity measurements for *in situ* use applied to civil engineering structures [43]. This point has not been addressed in the context of this paper, whose subject is

the development of tools usable *in situ* or in a supervision program (i.e. without reverse analysis).

The objective of this section is to propose a method for obtaining pseudo-sections of apparent resistivity in the context of a measurement carried out on a reinforced concrete structure. The methodology used is strongly inspired by the techniques used in the field of geophysics. The methods applied in this context are briefly described and the necessary adaptations to the field of civil engineering highlighted.

#### 346 4.1. Apparent resistivity in geophysics: practice and limits

In geophysics, the measurements of the electric potential differences are displayed through the apparent resistivity defined with equation (3) where the geometric factor *G* is determined so that the apparent resistivity is equal to the true resistivity when the medium is homogeneous. In the case of the semi-infinite medium as it is encountered in geophysics, the geometric factor can be defined analytically (see section 3.1). When the studied space is not homogeneous, the apparent resistivity gives only an approximate representation of the true resistivity [3, 2].

The apparent resistivity is displayed in the 2D space at data points with cartesian coordinates (x, z). The *x*-coordinate is obtained with the *x* positions of the electrodes, for instance for a Wenner device, *x* is the middle of the 4 electrodes. The *z*-coordinate is defined with a sensitivity analysis based on the Frechet derivatives. The sensitivity is studied as a function of the depth. By convention, the *z*-coordinate value corresponds to the depth (or distance to the sensor) where half of the Frechet derivative integral is obtained.

In the present study, the medium is not semi-infinite and consequently, first we have to assess the geometric factor, and second we cannot compute the Frechet derivatives. We thus propose to assess the geometric factor by considering the geometry of the monitored domain and the presence of the wire mesh and the sensor (see section 4.3.1) and we propose an approach, that mimics the analytical approach where the apparent resistivity coefficients result from a sensitivity analysis using an approximation of the solution of the resistivity problem (section 4.2).

<sup>365</sup> 4.2. Proposed methodology for displaying the apparent resistivity for any geometry

366 4.2.1. Parametrization

In this section, we propose a methodology to display the apparent resistivity for any electrostatic problem. It is based on a sensitivity analysis of the electric potential differences with

respect to the resistivity where the resistivity is simply modeled with constant coefficients by 369 blocks. Let  $\rho_i$  with  $i \in I = (1, \dots, d)$  be the resistivity coefficients allocated to the d disjointed 370 blocks of the medium and let  $\Delta V^j$ ,  $j = 1, \dots, m$ , the electric potential differences that solve the 371 electrostatic problem using this parametrization. By considering a finite range of possible values 372 for each resistivity coefficient, we introduce sensitivity indices that quantify the part of the vari-373 ance of  $\Delta V^{j}$  due to the variability of  $\rho_{i}$  and that are derived from the Sobol indices  $\frac{\operatorname{Var}(\mathbb{E}(\Delta V^{j}|\rho_{i}))}{\operatorname{Var}(\Delta V^{j})}$ . 374 In this expression, the conditional expectation  $\mathbb{E}(\Delta V^{j}|\rho_{i})$  represents the function of  $\rho_{i}$  only which 375 best approximates  $\Delta V^j$ , its variance Var( $\mathbb{E}(\Delta V^j | \rho_i)$ ) thus measures the fluctuation of  $\Delta V^j$  as if it 376 were a function of  $\rho_i$  only, and it is normalized by the total fluctuation of  $\Delta V$  [44]. Here we rather 377 use indices normalized with the maximal variance of the potential differences to better consider 378 the most influenced measures: 379

$$S_i^j = \frac{\operatorname{Var}(\mathbb{E}(\Delta V^j | \rho_i))}{\max_{l=1,\dots,m}(\operatorname{Var}(\Delta V^l))}.$$
(6)

- The sensitivity indices can be computed using Monte Carlo simulation methods [45] or using approximations of  $\Delta V^{j}$  on functional bases [46].
- The blocks are sized so to have an equivalent influence over the measurements, *i.e.* such that  $S_i = \sum_{i=1}^m S_i^j$  are of the same order for all of the blocks  $i \in I$ .

## 384 4.2.2. Calculation and display of the resistivity

We finally define the apparent resistivity  $\rho_{app,i}$  displayed in block *i* as a weighted sum of the measured apparent resistivities with respect to the sensitivity indices:

$$\rho_{app,i} = \frac{\sum_{j=1}^{m} S_{i}^{j} \rho_{app}^{j}}{\sum_{i=1}^{m} S_{i}^{j}}$$
(7)

with  $\rho_{app}^{j}$  the measured apparent resistivity related to the measured electricity potentials  $\Delta V^{j}$ with the relation (3) in which the geometric factor *G* is determined *a priori* for the studied case.

4.3. Towards the application on the concrete structure: preprocessed parameters for the display
 of the apparent resistivity

389 4.3.1. Determination of the geometric factor

As mentioned above, the geometric factor G first needs to be determined according to equation (3). For the case of the concrete structure studied in the present paper, the geometric factor has been estimated using the geometry and boundary conditions of the surveyed part of the concrete structure, that includes the added concrete marked out in red on Figures 2 and 5 and the layer of concrete containing the wire mesh and the sensor. A finite element model reproducing
 these conditions was used to assess the geometric factor.

Let denote  $\Omega$  the domain occupied by the medium. Its boundary is composed of the outer boundary of the parallelepipedic domain and of the boundaries in contact with the wire mesh and the sensor the geometries of which are modeled faithfully. The electric potential is the solution of problem (8):

$$\nabla \cdot \left(-\frac{1}{\rho} \overrightarrow{\nabla} V\right) + \delta_A I - \delta_B I = 0 \quad \text{in the medium,}$$
  
$$-\frac{1}{\rho} \overrightarrow{\nabla} V \cdot \vec{n} = 0 \quad \text{on the outer boundary of the domain,}$$
  
$$-\frac{1}{\rho} \overrightarrow{\nabla} V \cdot \vec{n} = 0 \quad \text{on the boundary of the sensor,}$$
(8)  
$$V = 0 \qquad \text{on the boundary of the wire mesh,}$$

where  $\rho$  is the resistivity and  $\delta_A I$  and  $\delta_B I$  are punctual sources of electric current I and -I imposed by the electrodes at points A and B.

For the determination of the geometric factors, we consider a homogeneous medium of known resistivity  $\rho$  and impose a current intensity I = 1 A. We then compute the electric potential differences  $\{\Delta V^j\}_{j=1}^m$  for the m = 117 positions of the electrodes with the Wenner device from which we deduce the geometric factors  $\{G^j\}_{i=1}^m$ .

#### 403 4.3.2. Parametrization of the numerical model

396

We consider the in situ concrete structure. Problem (8) is solved using the finite element 404 method. The resistivity is now considered non homogeneous and modeled with a piecewise 405 constant resistivity as presented in section 4.2.1 where the blocks are chosen so that the measure-406 ments are equally sensitive to each block. Figure 11 shows an example of the distribution of the 407 blocks for modeling the resistivity. The further the layers are from the sensor, the less influent 408 they are on the potential differential and thus the larger are the blocks. For the purpose of the 409 study which concerns the detection of a chloride front, we assume a uniform resistivity with re-410 spect to the y-axis. A single block along the y-axis to which we affect the resistivity identified 411 underneath the sensor (the surveyed area) is sufficient to model the medium. 412

<sup>413</sup> The parameters of the problem used in the following sections are the resistivities of the <sup>414</sup> blocks.

To illustrate the importance of considering the true geometry for defining the *z*-coordinate to display the apparent resistivity, we compare the sensitivities of the electric potential differences



Figure 11: Model of the monitored concrete structure: example of distribution of the blocks for the modeling of the resistivity with equivalent influence on the measurements.

obtained in both cases: analytically with the Frechet derivatives on the semi-infinite medium 417 and numerically on the more realistic geometry of the surveyed part of the concrete structure 418 presented above. Figure 12 shows the sensitivities for three different distances of the electrodes: 419 35 mm (top Figure), 70 mm (middle Figure) and 105 mm (bottom Figure). The depth at which 420 the apparent resistivity is displayed using the Frechet Derivatives Sensitivities (FDS) of the semi-421 infinite case, that is half of the integral of the sensitivity curve, is represented with a solid red line. 422 The one obtained numerically by considering the more realistic geometry is represented with a 423 dashed red line. For close distances of 35 mm both sensitivities are in good agreements whereas 424 the electrodes are distant, the numerical sensitivity has a bimodal distribution contrary to the 425 semi-infinite case. This shows that we do not probe the medium only far away from the sensor 426 but also the medium close to the sensor. This is due to the actual conditions of the surveyed area 427 especially that of the underside of the concrete. 428

Since the part of the structure containing the steel reinforcement above the wire mesh is not 429 part of the structure we want to study, the numerical model is also used to make sure the sensor is 430 not sensitive to that upper part (and so not sensitive to the steel reinforcement), or in other words 431 to make sure that the 35 mm wire mesh is well designed to prevent current from flowing to the 432 other side of the wire mesh. To that aim, we have considered an enlarged domain of concrete by 433 adding a layer of concrete above the wire mesh in the numerical model and we have analyzed 434 its effects on the electric potential differences. Figure 13 shows the modeling with the layer of 435 concrete above the wire mesh. The electric potential differences is sensitive to the lower part 436 of the domain with a sensitivity index  $S_{lower} \approx 1$  and to the upper part of the domain with a 437 sensitivity index  $S_{upper} \approx 2.10^{-8}$  assessed numerically. The experimental setup thus fulfills the 438







b) Sensitivity for a 70 mm distance between electrodes





Figure 12: Sensitivity of the measurement with respect to the depth obtained analytically on the semi-infinite medium (FDS: Frechet Derivatives Sensitivity) and numerically on the more realistic geometry (NS: Numerical sensitivity). The red lines locate the half of the integral of the sensitivity (DHI).

#### 439 requirements.



Figure 13: Section A-A of the model used to study the influence of the part above the wire mesh.

#### 440 4.4. Validation of the method for displaying of the apparent resistivity

The method is validated on experimental and numerical cases for which the resistivity field is known *a priori*. The displayed apparent resistivity obtained with the proposed method is viewed to verify the similarity between the imposed and the displayed apparent resistivities first in a homogeneous medium and then in non homogeneous ones. In the following, the resistivity is displayed in the 2D section A-A drawn in Figure 11. The ordinate axis will correspond to the distance to the underside of the monitored concrete part and is equal to h - z, with z the distance to the sensor (as in section 4.1) and h = 0.12 m the distance of the sensor to the underside.

#### 448 4.4.1. Tests on homogeneous medium

Let first consider the numerical model governed by equations (8) with constant resistivity  $\rho = 80 \,\Omega m$  in the whole domain. The apparent resistivity coefficients  $\rho_{app,i}$  (Figure 14b) obtained with equation (7) for 62 blocks and using the geometric factors assessed numerically is compared to the imposed homogeneous resistivity (Figure 14a). As expected, looking at the displayed apparent resistivity  $\rho_{app,i}$  in the homogeneous case, the uniform resistivity is recovered to the machine precision.

<sup>455</sup> On Figure 14a, the dashed line defines the domain, joined underneath the sensor, the resistiv-<sup>456</sup> ity of which is the most influent on the measurements of electrical potential differences. As the <sup>457</sup> outer part is not influent on the measurements, it is removed from the plots in the following.

Same comparison is performed on two experimental cases with supposed homogeneous source water of resistivity 23  $\Omega$ m and mixture of source and distilled water of resistivity 92  $\Omega$ m. Figure 15 displays the apparent resistivities  $\rho_{app,i}$  obtained with equation (7) for 46 blocks



Figure 14: (a) Original resistivity imposed on the finite element model. (b) Pseudo section of apparent resistivity display by the method.

<sup>461</sup> in the influent domain. Figures 15a and b plot the results for the medium of resistivity 23  $\Omega$ m and <sup>462</sup> 92  $\Omega$ m respectively. Again in both cases the apparent resistivity is similar to the homogeneous <sup>463</sup> resistivity of the water.



Figure 15: Pseudo section of resistivity for homogeneous mixtures of water. (a) source water with resistivity 23  $\Omega$ m and (b) mixture of source and distilled water with resistivity 92  $\Omega$ m.

#### 464 4.4.2. Heterogeneous medium

Additional tests have been carried out on the numerical model with known imposed non homogeneous resistivity field. Figures 16 and 17 present results of the display method on two cases where the imposed resistivities have vertical and horizontal gradients respectively (left Figures). The corresponding displayed apparent resistivity  $\rho_{app,i}$  (right Figures) for 46 blocks in the influential domain are plotted in the right Figures. Although the values of the original resistivities are not exactly recovered because of the heterogeneity of the resistivity field, the

display method is able to catch the trends of the original resistivity. The proposed display method 471

is found efficient as these results are consistent with those obtained in geophysics in semi-infinite 472



Figure 16: Original resistivity with vertical gradient imposed on the finite element model (a) and corresponding map of apparent resistivity displayed by the proposed method (b).



Figure 17: Original resistivity with horizontal gradient imposed on the finite element model (a) and corresponding map of apparent resistivity displayed by the proposed method (b).

The mapping for displaying the apparent resistivity could also be adapted to other parametriza-474 tion methods. For instance one can refine the block distribution of the apparent resistivity but the 475 computation cost becomes quickly unaffordable when the number of parameters increases. 476

#### 5. Results and discussion 477

473

#### 5.1. In situ Monitoring of temperature and humidity 478

The on-site temperature measurement is a crucial data needed for the correction of the re-479 sistivity measurements [31, 32, 24] and an input for the maturity method. Figure 19 gives the 480

evolution of the temperature during the whole duration of the study. The measurements of the 3 sensors Pt11, Pt12 and Pt13 are very close showing a homogeneous distribution of the temperature along the beam. Daily variations (day-night cycles) and seasonal variations are visible respectively on Figures 18 and 19. On the same beam, the relative humidity measured in concrete in the lower zone is shown in Figure 18 and Figure 19.



Figure 18: Monitoring of temperature and relative humidity (RH) in beam 2 with time (0 to 60 days).

The structure was cast in three steps. The part containing the sensors was filled on day 0 and a first temperature peak appears about 12 hours later (see Figure 18). The central part of the beam was cast 9 days later. This operation is visible in Figure 18 where a second temperature peak reaches 20°C. Finally, a few days later, the slab is cast, which has the effect of slightly modifying the temperature in the lower part of the beam.

Relative humidity records begin 48 hours after concrete casting in the lower part of the beam.
 The humidity probes are positioned in concrete openings recapped immediately after insertion



Figure 19: Monitoring of temperature and relative humidity (RH) within beam 2 with time (0 to 18 months).

of the sensors. It is therefore a measure of the relative humidity inside a cavity of a few cubic 493 centimeters (about 10 cm<sup>3</sup>) in the concrete, but not a direct measure of water content in the poros-494 ity. The main information is that despite of temporary decreases, linked to the occasional rise 495 in temperature (during chemical reaction of the cement paste), the relative humidity increases in 496 the cavity to stabilize around 98% on day 50 (see Figure 18) then remains between 95 and 100% 497 (Figure 19). The water content of concrete is high as the underside elements of the structure 498 are regularly submerged or splashed during tidal cycles. A decrease of this relative humidity to 499 95% occured during the first summer (see Figure 19). This is an important indication that should 500 be taken into account when analyzing resistivity measurements. Indeed, a concrete with a high 501 water content naturally has a low resistivity. 502

#### 503 5.2. Material parameters

504 5.2.1. Porosity

The porosity of the concrete used *in situ* has been estimated at 12% accoording to the French standard NF P18-459 as mentionned in section 2.5. This porosity value is relatively low [36]. Porosity is one of main general durability indicators that can be used to estimate the durability of concrete structures exposed to chlorides. The determination of porosity is actually necessary to deduce the water saturation of concrete and its chloride content.

#### 510 5.2.2. Compressive strength

To determine the activation energy, following equation (1), data are analyzed at the end of the first day, since during 24 hours all specimens have been stored at the same temperature. Figure 20 shows the influence of the curing temperature on the compressive strength and Figure 21 shows the time-temperature transformation based on the calculation of equivalent age. The bars on the graph represent the standard deviation of three experimental measurements.

The value of activation energy  $E_a$  deduced from the superposition method was 24.4 kJ/mol. This value was used to assess equivalent time  $\tau(t; T, T_{ref})$  with  $T_{ref} = 20$  °C for the specimens cured at T = 10 °C and T = 45 °C and then the equivalent age  $\tau(t; T, T_{ref})$  of the *in situ* concrete as well as the value of *in situ* concrete strength  $f_c(t; T, T_{ref})$  (see Figure 21). We clearly see the logarithmic model trend of the compressive strength with the equivalent time whatever the temperature. The calculation is possible for all regions equipped with a temperature sensor. [47].



Figure 20: Compressive strength of concrete specimens as a function of the time *t* for three different curing temperatures  $T = 10 \degree \text{C}$ ,  $20 \degree \text{C} (T_{ref})$  and  $45 \degree \text{C}$ .



Figure 21: Compressive strength  $f_c(t; T, T_{ref})$  of concrete specimens as a function of the equivalent time  $\tau(t; T, T_{ref})$  for three different curing temperatures T = 10 °C, 20 °C ( $T_{ref}$ ) and 45 °C.

#### 522 5.3. Evolution of average resistivity

First, we analyze the evolution of the average apparent resistivity measured in the volume below a resistivity sensor. The apparent resistivity measurements in beam 1, under the RS21 and RS22 sensors, has thus been plotted over time in Figure 22. The average of the 117 measurements made with a sensor is calculated to obtain the constituent points of this curve. The error bar symbolizes the standard deviation of all the resistivity measurements yielded by the considered sensor.



Figure 22: Measured resistivity in situ  $\rho_T$ .

These data cannot be used directly. The signal is noisy due to thermal effects. It should therefore be corrected. One technique is to calculate the average apparent resistivity at a reference temperature  $T_{ref}$  (here 20 °C), according to equation (9):

$$\rho_T = \frac{\rho_{T_{\text{ref}}}}{1 + \alpha \left(T - T_{\text{ref}}\right)} \tag{9}$$

where  $\rho_T$  is the apparent resistivity measured at the temperature T and  $\rho_{T_{ref}}$  is the apparent resistivity computed for the temperature  $T_{ref}$ . The coefficient  $\alpha$  is a correction factor of temperature effects which is set here at 0.022 °C<sup>-1</sup> as proposed by Whittington and al.[6].

We chose 20 °C for the reference temperature since it is the temperature commonly used in 535 the literature for resistivity correction and also because it is the temperature used for the equiv-536 alent time calculation for material hardening. The corrected curves are plotted on Figure 23. 537 After the thermal correction, the resistivity evolutions are similar to those described by the au-538 thors who performed resistivity measurement in laboratory on concrete specimens [13, 11]. This 539 result contributes to validate the relevance of the measurements obtained with the in situ device 540 and the need for temperature measurement. It can also be noted that the two sensors embedded 541 in the same beam about 20 cm far from each other, give very similar apparent resistivities. 542



Figure 23: Resistivity  $\rho_{T_{ref}}$  computed at 20 °C.

An interesting property of the resistivity comes from its link to porosity. The porosity evolves with hydration [37] thus modifying the resistivity value. Since, the mechanical strength of concrete is influenced by porosity, the resistivity measurement can be considered as an indicator of material hardening. This appears clearly on Figure 24 on which the mechanical strength is plotted as a function of the average electrical resistivity. The relationship between these two quantities is a linear relationship with a correlation coefficient very close to 1.



Figure 24: Evolution of compressive strength  $f_c(t; T, T_{ref})$  as a fonction of electrical resistivity  $\rho_{T_{ref}}$  for  $T_{ref} = 20$  °C.

According to Archie [4], the electrolytic resistivity of the material is given by the following empirical law:

$$\rho = a\rho_w \Phi^{-m} S_r^{-n} \tag{10}$$

with  $\rho$  the electrolytic resistivity of concrete (in  $\Omega$ .m),  $\rho_w$  the resistivity of the interstitial 30

solution (temperature dependent),  $\Phi$  the porosity of the material,  $S_r$  the degree of saturation, and where *a*, *m* and *n* are material parameters.

In this study it is assumed that the concrete is saturated with water. This assumption seems reasonable considering the environment of the structure and the relative humidity measurements made in the concrete beams. Indeed, the relative humidity variations are low and RH% remains very high over time. So  $S_r$  is considered equal to 1 in equation 10.

The electrical resistivity of a water-saturated concrete is then a function of the following parameters: pore volume, porous connectivity, cement type (here the same for the two beams), degree of hydration and chemical composition of the pore solution (parameter  $\rho_w$ ).

In a healthy concrete, in the absence of chlorides, the influence of the chemical composition 561 of the pore solution remains small if the solution remains alkaline [36] and thus  $\rho_w$  does not 562 vary. The electrical current propagates mainly through the saturated porous network. The most 563 influent parameter on resistivity measurement is therefore the connectivity of the pore network 564 (since the influence of temperature has been previously corrected). The measurement of elec-565 trical resistivity is therefore a simple way to characterize indirectly the connectivity of a porous 566 saturated medium  $\Phi^{-m}$ . For a given cement paste, the reduction of porosity due to the hydration 567 of cement results in the same time in a decrease in pore connectivity, and an increase in strength. 568 The morphology of cement paste depends on cement type and concrete composition, thus there 569 is not a general correlation between resistivity and strength (see [48]). Here the same concrete 570 was used for both measurements. This explains the excellent correlation between the mechanical 571 strength measurement and the resistivity measurement observed in Figure 24. 572

<sup>573</sup> On Figure 25, the compressive strength  $f_c(t; T, T_{ref})$  is drawn together with the resistivity  $\rho_{T_{ref}}$ <sup>574</sup> as a function of equivalent time  $\tau$ . Both curves exhibit a similar evolution. They have especially <sup>575</sup> similar inflection. As a consequence, when the resistivity has reached its asymptotical value, it <sup>576</sup> can be said that the concrete has almost reached its maximum compressive strength.

Simultaneous monitoring of the evolutions of the mechanical properties of concrete and of the resistivity shows that resistivity sensors could be used as part of a strategy to optimize the phasing of the construction process. Obtaining such a result *in situ*, already known and documented in laboratory tests, is particularly interesting because it reinforces the interest of using an embedded resistivity measurement device at early age and not only for chloride assessment. Indeed, both the constructor of the structure, within the framework of the monitoring of manufacturing processes,



Figure 25: Evolutions of compressive strength  $f_c(t; T, T_{ref})$  and of electrical resistivity  $\rho_{T_{ref}}$  as functions of equivalent age  $\tau$  for  $T_{ref} = 20$  °C.

and the owner of the structure, within the framework of the ageing structure survey, could find
 an advantage in using this measuring system which reinforces the interest of *in situ* installation
 of DC measurement devices.

#### 586 5.4. Displaying the pseudo-sections of apparent resistivities

The pseudo-sections of apparent resistivities displayed following the procedure described in section 4.2 are presented in Figure 26 for days 2, 30 and 426 after concrete casting. The appearance of the pseudo resistivity sections displayed with a given sensor is very similar from one day to another in terms of gradients.

It can also be noted that the dispersion of the resistivity measurements around the mean value 591 is much higher than that observed in the water and also much higher than the repeatability error 592 measured in situ in concrete (see section 3.2). The variability of apparent resistivities cannot 593 therefore be explained solely by measurement errors. This variability in resistivity is related 594 to the heterogeneity of the material; the most likely explanation is the variability of porosity. 595 This would explain why the facies of the resistivity maps change only slightly over time once 596 the main chemical reactions have occurred during the very first days of concrete setting and 597 hardening. Conversely, as shown in the previous section, the average resistivity value increases 598 with time which is also consistent with the porosity evolution. 599

Furthermore, it can be noted that the values of apparent resistivity are very low. Although it is not possible to state that concrete is saturated with water only on the basis of a relative humidity



Figure 26: Pseudo sections of resistivity. From left to right: RS21 and RS22 sensors. From top to bottom: days 2, 30 and 426.

measurement in a cavity, the water content of concrete is likely to be very high. This assumption is consistent with the low resistivity values measured on site while the porosity of the concrete measured in laboratory is low (see section 5.2). The values of the resistivities found here are also consistent with the observations of previous work on the topic[13, 49].

An indicator of corrosion probability based solely on the evolution of the average resistivity 606 value does not seem to be the most appropriate choice for application to a port or offshore struc-607 ture if one refers to the observations made on the wharf (porosity, resistance, relative humidity, 608 temperature and resistivity measurement). Since a pseudo section of apparent resistivity appears 609 to be a characteristic of the material properties in a given area, it is proposed to study the differ-610 ence between the pseudo sections at two different times. This difference is shown on the Figure 611 27 on which the resistivity difference obtained for the two sensors RS21 and RS22 on days 114 612 and 148 is displayed (difference and relative difference). 613



Figure 27: Pseudo section of difference of resistivity. Left: difference of the resistivity of the RS21 sensor between the days 114 and 148. Right: relative difference of the resistivity of the RS21 sensor between the days 114 and 148.

614

The difference between the apparent resistivities measured on days 114 and 148 is positive

at any point of the pseudo section of apparent resistivity. This is an expected result and this 615 result was found for all ages and sensors. Over time, the water content of concrete is expected 616 to decrease rapidly after the dormant period and then to decrease more and more slowly as the 617 hydration of cement consumes water. A local decrease in resistivity between two time periods 618 (excluding artifacts related to poor temperature compensation) would mean that the concrete 619 has become wetter or that its chemical composition has changed (for example, due to chloride 620 ion penetration). The sign of the difference between two pseudo sections of apparent resistivity 621 appears to be a good indicator of early detection of corrosion. It should be noted, however, 622 that with a pseudo section of apparent resistivity, it would not be possible to accurately define 623 the size of the affected area and its precise distance from the surface. However, this is a good 624 indicator to state almost instantly, - within the framework of a sensor integrated into an SHM 625 chain - and with great certainty that concrete is evolving and that monitoring in the area must 626 be strengthened. Further actions could then be done. In some cases coring concrete specimens 627 could be necessary. 628

#### 629 6. Conclusion and outlook

Electrical resistivity measurements are currently used in the field of inspection of civil engineering structure, mainly as part of a one-time measurement campaign using portable Wenner probes. The performance of these devices is limited by the difficulty of obtaining repeatable contact between the electrode and the concrete surface on the one hand and by the presence of reinforcement on the other hand. The intrinsic heterogeneity of concrete also complicates the analysis of measurements, making it difficult to interpret localized measurements.

Embedded sensors in concrete structures during casting solves the problem of poor repeata-636 bility measurement induced by resistance contact between concrete and electrode. However, the 637 problem of taking into account the influence of the presence of reinforcements on the measure-638 ment remains. This topic is the subject of current work with variable solutions depending on the 639 nature and geometry of the measuring device used [13, 50, 30]. The first objective of this paper 640 was to propose an installation methodology of a multi-electrode sensor embedded in concrete to 641 avoid the influence of reinforcements on measurements. To that aim, the resistivity sensor was 642 attached to a wire mesh that confines the electric current in the concrete cover area. In this study, 643 we chose to use a multi-electrode sensor about one meter long interrogated with a Wenner alpha 644

protocol to obtain a hundred resistivity measurements in the monitoring area. All the measures 645 available thus allow the intrinsic heterogeneities of the concrete studied to be taken into account. 646 The evolution of the average resistivity value over time was compared with the evolution of the 647 mechanical strength of *in situ* concrete estimated using the maturometry method. This *in situ* re-648 sult tends to prove the relevance of the proposed method of sensor installation and calibration and 649 also opens the perspective to use resistivity measurement, not only within the framework of age-650 ing survey but also within the framework of concrete hardening monitoring for the optimization 651 of the construction process. 652

Then, the second goal of this article was to propose a method for analyzing and displaying 653 resistivity measurements in the form of a pseudo section of apparent resistivity. It is based on the 654 numerical evaluation of the sensitivity of potential measurements to resistivity variations in pre-655 defined volume blocks according to their influence on the measurements. The methodology has 656 been validated and applied to the analysis of resistivity measurements performed on a new port 657 wharf for 18 months. The heterogeneous and random nature of the resistivity was attributed to the 658 heterogeneity of the porosity of the concrete. It was thus considered that these maps presented 659 information intrinsic to each studied zone and proposed an indicator of corrosion probability 660 based on the study of the difference between two pseudo-sections of apparent resistivity. Since it 661 allows instant visualization of results, the display of apparent resistivity maps can be integrated 662 into an *in situ* measurement system or into a structure supervision system. If an anomaly is de-663 tected by comparing the apparent resistivity sections between two days, several actions can be 664 taken, including coring or computation of the true resistivity for a more accurate location of the 665 anomaly. In this case, the apparent resistivity can be used for initialization in the optimization 666 algorithms for the identification of the true resistivity. With the methodology proposed here, it 667 is possible to provide a set of initial parameters close to the final solution, which contributes to 668 improving the efficiency of inversion algorithms. 669

Resistivity is an indirect indicator of corrosion. When the resistivity value is below a threshold value, the probability of corrosion initiation is considered high. The use of on-site resistivity
is in most cases limited to the detection of risk areas. To obtain reliable information on the
corrosion of the reinforcement and the position of the chloride front, destructive tests (chloride
titration) are traditionally carried out.



order to characterize the degree of corrosion, through the relationships between:

677

• the resistivity value and the chloride content [51];

• the resistivity value and the value of the diffusion coefficient of chloride ions in concrete [38, 14];

• the resistivity value and the current corrosion value [52].

Associated together, the value of the chloride rate in a given area and the diffusion coefficient of chloride in concrete make it possible to obtain predictions over structure life duration by calculation [52].

The measurement of the corrosion current is a direct indicator. It will be interesting during the service life of the structure to compare the resistivity measurements and the predicted advance of the chloride front with measurements of reinforcement electric potential. This study will be the continuation of this work.

#### 689 Acknowledgment

The authors would like to thank all the partners of iMAREO2 project: Keops Automation (D. Follut, D. Olivier), Université de Nantes (M. Roche), Nantes – Saint Nazaire Port (P. Lijour, M. Labegorre) and Bouygues Construction (the teams of Bouygues Travaux Publics Régions France). The authors would like to thank the Pays de la Loire region for its financial support.

#### 694 **References**

- [1] Harsh K. Gupta, editor. *Encyclopedia of Solid Earth Geophysics*. Encyclopedia of Earth Sciences Series. Springer
   Netherlands, 2011.
- M.H. Loke. Electrical imaging surveys for environmental and engineering studies A practical guide to 2-D and 3-D
   surveys. Technical report, 2000.
- [3] W.M. Telford, P.L. Geldart, and R.E. Sheriff. *Applied geophysics 2nd edition* | *Solid earth geophysics*. Cambridge University Press, 1991.
- [4] G. E. Archie. The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics. *Transactions of the AIME*, 146(01):54–62, December 1942.
- [5] G. E. Archie. Classification of Carbonate Reservoir Rocks and Petrophysical Considerations. AAPG Bulletin,
   36(2):278–298, 1952.
- [6] H. W. Whittington, J. McCarter, and M. C. Forde. The conduction of electricity through concrete. *Magazine of Concrete Research*, 33(114):48–60, March 1981.
- [7] Samuel Naar. Evaluation non destructive du beton par mesures de resistivite electrique et thermographie infrarouge
   passive. thesis, Bordeaux 1, January 2006.
- [8] J.F. Lataste, C. Sirieix, D. Breysse, and M. Frappa. Electrical resistivity measurement applied to cracking assessment on reinforced concrete structures in civil engineering. *NDT & E International*, 36(6):383–394, September 2003.

- [9] Zhiyong Liu, Yunsheng Zhang, and Qian Jiang. Continuous tracking of the relationship between resistivity and pore structure of cement pastes. *Construction and Building Materials*, 53:26–31, February 2014.
- [10] M. Saleem, M. Shameem, S. E. Hussain, and M. Maslehuddin. Effect of moisture, chloride and sulphate contamination on the electrical resistivity of Portland cement concrete. *Construction and Building Materials*, 10(3):209–214, April 1996.
- [11] Wolfgang Brameshuber, Christoph Dauberschmidt, Petra Schroder, and Michael Raupach. Non-destructive de termination of the water content in the concrete cover using the multi-ring-electrode. Technical Report RWTH CONV-006116, DGZfP, 2003.
- [12] Effect of moisture content on concrete resistivity measurement. *Journal of the Chinese Institute of Engineers*, 25:117–122, January 2002.
- Rob B Polder. Test methods for on site measurement of resistivity of concrete a rilem tc-154 technical recommen dation. *Construction and Building Materials*, 15(2):125–131, March 2001.
- Rob B Polder and Willy H. A Peelen. Characterisation of chloride transport and reinforcement corrosion in concrete under cyclic wetting and drying by electrical resistivity. *Cement and Concrete Composites*, 24(5):427–435, October 2002.
- [15] W Morris, A Vico, M Vazquez, and S. R de Sanchez. Corrosion of reinforcing steel evaluated by means of concrete resistivity measurements. *Corrosion Science*, 44(1):81–99, January 2002.
- [16] Jean-François Lataste. Évaluation non destructive de l'état d'endommagement des ouvrages en béton armé par
   mesures de résistivité électrique. Bordeaux 1, January 2002.
- [17] C Andrade, M Castellote, and R d'Andrea. Chloride aging factor of concrete measured by means of resistivity.
   Porto Portugal, April 2011.
- [18] Yann Lecieux, Franck Schoefs, Stéphanie Bonnet, Trystan Lecieux, and Sergio Palma Lopes. Quantification and
   uncertainty analysis of a structural monitoring device: detection of chloride in concrete using DC electrical resis tivity measurement. *Nondestructive Testing and Evaluation*, 30(3):216–232, July 2015.
- [19] Yanbo Liu, Francisco Presuel-Moreno, and Mario Paredes. Determination of Chloride Diffusion Coefficients in Concrete by Electrical Resistivity Method. *ACI Materials Journal*, 112(5), October 2015.
- [20] Milia Fares, Géraldine Villain, Stéphanie Bonnet, Sergio Palma Lopes, Benoit Thauvin, and Mickael Thiery. Determining chloride content profiles in concrete using an electrical resistivity tomography device. *Cement and Concrete Composites*, 94:315–326. November 2018.
- [21] Pejman Azarsa and Rishi Gupta. Electrical Resistivity of Concrete for Durability Evaluation: A Review. Advances
   *in Materials Science and Engineering*, 2017:1–30, 2017.
- [22] Jean-François Lataste, Géraldine Villain, and Jean-Paul Balayssac. Electrical Methods. In *Non-Destructive Testing and Evaluation of Civil Engineering Structures*, pages 139–172. Elsevier, 2018.
- R. du Plooy, S. Palma Lopes, G. Villain, and X. Dérobert. Development of a multi-ring resistivity cell and multielectrode resistivity probe for investigation of cover concrete condition. *NDT & E International*, 54(Supplement C):27–36. March 2013.
- [24] W. J. McCarter, T. M. Chrisp, G. Starrs, P. A. M. Basheer, and J. Blewett. Field monitoring of electrical conductivity of cover-zone concrete. *Cement and Concrete Composites*, 27(7):809–817, August 2005.
- [25] J.F. Lataste, T. De Larrard, F. Benboudjema, and J. Semenadisse. Study of electrical resistivity: variability assessment on two concretes: protocol study in laboratory and assessment on site. *European Journal of Environmental and Civil Engineering*, 16(3-4):298–310, April 2012.
- [26] J-F. Lataste and D. Breysse. A Study on the Variability of Electrical Resistivity of Concrete. In Gunes Oguz and
   Yillmaz Akkaya, editors, *Nondestructive Testing of Materials and Structures*, pages 255–261. Springer Nether lands, Dordrecht, 2013.
- <sup>756</sup> [27] Lucas Bourreau. *Diagnostic de corrosion sur ouvrage : fiabilite et aide a la decision*. Nantes, December 2017.
- <sup>757</sup> [28] Ueli M. Angst and Rob Polder. Spatial variability of chloride in concrete within homogeneously exposed areas.
   <sup>758</sup> *Cement and Concrete Research*, 56:40–51, February 2014.
- [29] S G Millard and WENNER. REINFORCED CONCRETE RESISTIVITY MEASUREMENT TECHNIQUES.
   *Proceedings of the Institution of Civil Engineers*, 91(1):71–88, March 1991.
- [30] Gabriel Samson, Fabrice Deby, Jean-Luc Garciaz, and Jean-Louis Perrin. A new methodology for concrete resis tivity assessment using the instantaneous polarization response of its metal reinforcement framework. *Construction and Building Materials*, 187:531–544, October 2018.
- [31] T. M. Chrisp, G. Starrs, W. J. McCarter, E. Rouchotas, and J. Blewett. Temperature-conductivity relationships for concrete: An activation energy approach. *Journal of Materials Science Letters*, 20(12):1085–1087, 2001.
- [32] Marta Castellote, Carmen Andrade, and Mari Cruz Alonso. Standardization, to a Reference of 25 C, of Electrical Resistivity for Mortars and Concretes in Saturated or Isolated Conditions. *Materials Journal*, 99(2):119–128, March 2002.
- [33] N. Wiwattanachang and P.H. Giao. Monitoring crack development in fiber concrete beam by using electrical resistivity imaging. *Journal of Applied Geophysics*, 75(2):294–304, October 2011.

- 771 [34] P. K. Mehta. CONCRETE. STRUCTURE, PROPERTIES AND MATERIALS. 1986.
- [35] RILEM Technical Committee 108. Interfacial transition zone in concrete: state-of-the-art report. E & FN Spon,
   London New York, 1996.
- [36] Véronique Baroghel-Bouny. Conception des bétons pour une durée de vie donnée des ouvrages. Technical report,
   Association Française de Génie Civil, 2004.
- [37] Nicolas Burlion, Frédéric Bourgeois, and Jian-Fu Shao. Effects of desiccation on mechanical behaviour of concrete.
   *Cement and Concrete Composites*, 27(3):367–379, March 2005.
- [38] Ozkan Sengul. Use of electrical resistivity as an indicator for durability. *Construction and Building Materials*,
   779 73:434–441, December 2014.
- [39] Laboratoire central des ponts et chaussees. *Resistance du beton dans l'ouvrage: la maturometrie.* LCPC, Paris,
   2003. OCLC: 54835566.
- [40] A. G. A. Saul. Principles underlying the steam curing of concrete at atmospheric pressure. *Magazine of Concrete Research*, 2(6):127–140, March 1951.
- [41] European Committee for Standardisation. Eurocode 2: Design of concrete structures Part 1-1: General rules and
   rules for buildings, 2004.
- [42] P Freiesleben Hansen and E.J. Pedersen. Maleinstrument til Kontrol af betons haerdning. Nordisk betong, 1:21–25,
   1977.
- [43] Jean Paul Balayssac and Vincent Garnier. Non-destructive Testing and Evaluation of Civil Engineering Structures
   1st Edition. ISTE Press Elsevier, 2017.
- [44] I.M Sobol. Global sensitivity indices for nonlinear mathematical models and their monte carlo estimates. *Mathematics and Computers in Simulation*, 55(1-3):271–280, 2001.
- [45] A. Saltelli, P. Annoni, I. Azzini, F. Campolongo, M. Ratto M., and S. Tarantola. Variance based sensitivity analysis
   of model output. design and estimator for the total sensitivity index. *Computer Physics Communications*, 181:259–270, 2010.
- From Sudret. Global sensitivity analysis using polynomial chaos expansions. *Reliability Engineering & System Safety*, 93(7):964 979, 2008. Bayesian Networks in Dependability.
- Tahsin Alper Yikici and Hung-Liang (Roger) Chen. Use of maturity method to estimate compressive strength of
   mass concrete. *Construction and Building Materials*, 95(Supplement C):802–812, October 2015.
- [48] Ali Akbar Ramezanianpour, Amirreza Pilvar, Mahdi Mahdikhani, and Faramarz Moodi. Practical evaluation of
   relationship between concrete resistivity, water penetration, rapid chloride penetration and compressive strength.
   *Construction and Building Materials*, 25(5):2472–2479, May 2011.
- [49] A. Lubeck, A.L.G. Gastaldini, D.S. Barin, and H.C. Siqueira. Compressive strength and electrical properties of
   concrete with white Portland cement and blast-furnace slag. *Cement and Concrete Composites*, 34(3):392–399,
   March 2012.
- [50] Mustafa Salehi, Pouria Ghods, and O. Burkan Isgor. Numerical investigation of the role of embedded reinforce ment mesh on electrical resistivity measurements of concrete using the Wenner probe technique. *Materials and Structures*, 49(1-2):301–316, January 2016.
- [51] W Morris, A Vico, and M Vazquez. Chloride induced corrosion of reinforcing steel evaluated by concrete resistivity
   measurements. *Electrochimica Acta*, 49(25):4447–4453, October 2004.
- [52] Michael D. A. Thomas and Phil B. Bamforth. Modelling chloride diffusion in concrete: Effect of fly ash and slag.
   *Cement and Concrete Research*, 29(4):487–495, April 1999.