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New optimization algorithm for optimal spatial sampling during non-destructive testing of concrete structures

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ABSTRACT

Non-destructive Testing (NDT) techniques are essential in order to assess properties or detect anomalies (cracks, pathologies, etc.) in concrete during the diagnosis of structures. However, due to budget limitations, an optimal methodology to estimate the integrity of a structure at minimum cost is required. This paper presents a spatial optimization of NDT measurements (ultrasound) based on their spatial correlation. The optimization is performed in two steps. First, the relationship between the number of measurements organized in a regular grid and the fitness function value are determined using spatial interpolation (kriging method). Then, using an Optimization Spatial Sampling Method developed for this study (OSSM), the fitness function is minimized by changing the positions of a chosen number of NDT measurements. The theoretical development and the results obtained with both simulated and real data are presented and discussed.

1. Introduction

Nowadays, most of the structures for human use (buildings, bridges, etc.) are made of concrete. It is of vital importance to ensure that they function correctly during their service life and it has become crucial to find a reliable and efficient method for evaluating the condition of a structure at different times of its life span. Traditionally, the most commonly used method for the evaluation of a concrete structure has been visual inspection [1]. It is usually carried out by an expert engineer, who defines the most degraded zones of the structure and takes some samples (cores) in order to refine his analysis and eventually propose a reparation procedure. This method, which is subjective and remains informal, can only be used when a number of pathologies in the concrete, like cracking and spalling, are visible. Other pathologies, such as reinforcing steel corrosion are difficult to identify with visual inspection alone. For that reason, non-destructive testing is an interesting complement in the diagnosis of a concrete structure [2–7].

Non-destructive Testing (NDT) started to be used in reinforced concrete structures due to the increasing need to objectively evaluate their condition. The aim was also to manage the safety of the structure and to eventually set up a maintenance plan [8–10]. NDT also opened up the possibility of preventive maintenance, which is three to twenty times less expensive than repair in terms of energy and financial resources [11].

NDT techniques are sensitive not only to anomalies in the concrete but also to its physical and mechanical properties. For instance, ultrasound, impact-echo and rebound hammer are used to assess the concrete compressive strength, while electrical resistivity and GPR are sensitive to water content. Moreover, concrete inhomogeneity often leads to spatial variability in structures [12–15]. In addition, recent reliability studies have shown that the spatial correlation may govern the reliability of structural components [16]. Some studies have been carried out with the aim of analyzing spatial variability but, to the best of our knowledge none of them has focused on sampling optimization for optimal inspection.

Among NDT techniques, some, such as ultrasonic pulse velocity, rebound hammer, and GPR, etc. are fast and inexpensive. The general frame that we promote is that of a two-step approach where a fast technique is first used to obtain a general view of the spatial distribution for a particular property of the concrete (strength, moisture, etc.), and where the critical zones can be analyzed more into details in a second step, with NDT measurements of higher quality and/or cores. This approach takes advantage of the two types of ND investigations (fast and slow) and destructive testing while keeping the cost/benefit ratio within reasonable limits.

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Notations

ANR	National agency of research
C2D2-ACDC	Designing and building for sustainable development – Capitalization and analysis for the diagnosis of constructions
EDF	French electricity company
EVADEOS	Non-destructive evaluation for the prediction of reinforced concrete structures degradation and their monitoring
FFV	fitness function value
FFV_o	initial fitness function value
FFV_f	final fitness function value
GPR	Ground Penetrating Radar
MAC	Metropolis Accepting Criterion
MKSD	Mean Kriging Estimation Error Standard Deviation
MPE	Mean Prediction Error
NDT	Non-destructive Testing
OIS	optimal inspection strategy
OSSM	Optimal Spatial Sampling Method
SSA	Spatial Simulated Annealing
UPV	ultrasonic pulse velocity
VEE	Variance Estimation Error

Nonetheless, to maximize the contribution of NDT techniques or coring procedure in a previously investigated structure, it is imperative to carry out optimal spatial sampling for localizing the most critical zones in order to optimize the diagnosis.

This paper presents a new idea for the diagnosis of reinforced concrete structures based on an original methodology of NDT spatial sampling optimization, making use of geostatistical tools such as the variogram and kriging, and developing an algorithm inspired on the Spatial Simulated Annealing (SSA) [17], which is used for geostatistical applications [18]. SSA has been used for instance in other domains such as measuring radioactivity releases [19], and ecosystem studies [20]. However, this algorithm has never been used on concrete structures studies.

This approach offers a new solution for a very important problem in concrete structure evaluation and can be applied to any NDT technique and to a large variety of NDT techniques and concrete structures as bridges, buildings, tunnels, nuclear plants, etc. An original Optimization Spatial Sampling Method (OSSM) was developed and tested with three different fitness functions: the mean kriging standard deviation, the mean prediction error and the variance estimation error. The performance of the OSSM was explored (a) with simulated 2D data inferred from a specified spatial correlation (variogram) and (b) with ultrasonic pulse velocity measurements obtained on a horizontal profile of a wall of a thermal power plant located in Le-Havre, France.

2. Presentation of the strategy

For the structure manager, it is important to regularly assess the condition of the structure to know when he must proceed to some maintenance or reparations. Visual inspection is not enough or might be inadequate, while several NDT measurements are time consuming and expensive. Taking cores throughout the structure is not just expensive, but it would also affect structural stability and safety. In addition, the results provided by NDT remain local information and cannot be generalized to the whole structure. Hence, a good compromise between different inspection strategies would be required to classify and evaluate accurately the maintenance and/or repair zones in the structure, accounting for both time and cost efficiency.

To define an appropriate maintenance/reparation strategy at a minimum cost, it is necessary to implement an optimal inspection strategy (OIS). This strategy consists of carrying out first a pre-auscultation of the structure under test, using a "fast" and low cost NDT to evaluate and model the spatial variability. In a second step, the Optimization Spatial Sampling Method (OSSM) developed for this study will make possible to define the number and the optimal locations of more refined measurements or of samples to be taken for complementary diagnosis or future monitoring of the concrete structure.

The OSSM, which will be fundamental to the planning of an OIS, uses the spatial correlation and variability of NDT to evaluate the mechanical properties of a concrete structure in the best way possible, using a combination of fast and low cost NDT, higher quality NDT, and eventually coring in order to reach a relevant diagnosis of the actual condition of the concrete structure at an acceptable cost/benefit ratio (Fig. 1).

Two geostatistical tools (variogram and kriging) were used as well as the OSSM. Their fundamental principles are presented in the following section.

2.1. Spatial correlation – variogram

There is usually some spatial variability in a concrete structure because of the concrete inhomogeneity and the variability of the exposure conditions [12–16]. However, most of the time, it can be said that, for a given number of measurements distributed on a surface, two close measurements have a higher similarity than two more distant ones. This spatial dependence can be represented by a statistical function known as the variogram [21], which is defined as half the variance of the difference between two data items from two different locations separated by a distance h (1).

$$\gamma(h) = \frac{1}{2} Var[Z(x) - Z(x+h)] \tag{1}$$

For a series of observed measurements with a limited series of pairs separated by a distance h ($N(h)$), an empirical variogram can be determined as:

$$\gamma_e(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} Var[Z(x_i) - Z(x_i+h)]^2. \tag{2}$$

For each empirical variogram, a model can be fitted by the least squares method to obtain a mathematical function that can be used later to compute the expected value of the measurement at any additional point. Fig. 2 shows an example of a variogram model (spherical type) which can be fitted to the experimental variogram (3):

$$\begin{aligned} \gamma(h) &= (Co + C)\left[1.5\frac{h}{a} - 0.5\left(\frac{h}{a}\right)^3\right] \quad \text{if } 0 < h < a \\ \gamma(h) &= Co + C \text{ if } h > a \end{aligned} \tag{3}$$

In Eq. (3), three main parameters can be inferred: nugget (Co) that describes the variance of a measurement made several times at the same location (uncertainty due to lack of repeatability), sill ($Co + C$) that represents the global half variance (global variability of the material tested on the structure), and range (a) which represents the maximum distance where data are correlated. The range is also called the correlation length, which provides information about the necessary sampling distance, such as to get statistically