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# The $\alpha\delta$ method for modeling NDT results in risk based inspection of corroded steel wharves

F. Schoefs<sup>1</sup> and J. Boéro<sup>2</sup>

**Abstract** – Owners of structures and infrastructure base their maintenance decision schemes mainly on structural integrity assessment and consequence analysis. The major inputs come from information collected by inspections employing non-destructive or destructive tools. Uncertainties and errors of measurement can lead to bad decisions but these effects are rarely integrated into the decision making process. Risk Based Inspection (RBI) provides the basics for optimizing the maintenance plans of existing structures while ensuring satisfactory safety and availability of the structure during its service life. This basis depends both on computation of reliability index and probabilistic modeling of inspection results. Probabilistic modeling of inspection results leads to specifying the Probability of Detection (PoD), the Probability of False Alarms (PFA) and the Receiver Operating Characteristics (ROC) curve that are usually considered as key parameters in RBI. Under these circumstances the comparison of Non destructive Testing (NDT) tools in terms of cost/benefit is difficult to be established as well as the method for optimizing a given technique. This paper starts from the  $\alpha\delta$  method that gives a new performance indicator in this context, and apply it to the field of inspection of steel harbor structures, after a detailed analysis of uncertainties during corrosion assessment by ultrasonic measurements.

**Key words:** Ultrasonic testing / steel / risk management / corrosion / wharves

**Résumé** – La méthode  $\alpha\delta$  pour la modélisation des résultats CND pour l'inspection basée sur les risques de quais métalliques corrodés. Les gestionnaires de structures et d'infrastructures fondent leurs décisions de maintenance sur des analyses d'intégrité structurelle et des conséquences de défaillances. Les entrées principales de ces méthodes sont les inspections par contrôles destructifs ou non destructifs. Les erreurs de mesure peuvent conduire à de mauvaises décisions, celles-ci étant rarement prises en compte dans les analyses de risque. Les méthodes d'inspection basées sur les analyses des risques fournissent le cadre méthodologique d'optimisation des inspections. Les résultats dépendent de l'évaluation de la fiabilité et de la modélisation probabiliste des données d'inspection. Cette dernière est généralement basée sur l'évaluation des Probabilités de Détection, Probabilités de Fausses Alarmes et Courbes ROC. Au vu de la difficulté d'une évaluation précise de ces grandeurs, il reste difficile de disposer des outils d'optimisation du rapport coût/bénéfice ou de comparaison des techniques. Cet article s'appuie sur la méthode  $\alpha\delta$  qui fournit un indicateur de performance dans ce contexte appliqué au contrôle de la corrosion de palplanches métalliques ; on décrit et modélise en particulier les incertitudes de mesure par ultrasons selon différents protocoles.

**Mots clés :** Contrôle par ultrasons / acier / management des risques / corrosion / quais

## 1 Introduction

Replacement of engineering structures results in high economic and environmental costs, thus increasing the

interest in maintaining these structures with efficient management plans. Therefore, the challenge for owners consists in guaranteeing the operation and safety of ageing structures, while ensuring reasonable costs and

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availability conditions. Harbor structures meet all these conditions and challenges.

Reassessment of existing structures emphasizes the need for updated material properties with reliable techniques. Generally on-site inspections are necessary and in most of cases visual inspections are not sufficient. Non Destructive Testing (NDT) tools are then required. When inspecting large structures (bridges) or coastal and marine structures the natural environment (wind, waves) and human factors (access, tiredness, lack of experience, etc.) induce lower conditions for inspection in comparison to laboratory conditions. Coastal and marine structures are more affected due to the presence of marine growth (mussels, barnacles, algae, ...) and the dependence on a radio-link between the diver and the operator. Additionally, inspections in immersion areas are a problem as well. In these fields, the cost of inspection can be prohibitive and an accurate description of the on-site performance of NDT tools must be provided. When inspection of existing structures is not perfect, it has become a common practice to model their reliability in terms of Probability of Detection (PoD), Probability of False Alarms (PFA) and Receiver Operating Characteristic (ROC) curves [1–3]. These quantities are generally the main inputs needed by owners of structures who are looking to achieve the so-called IMR (Inspection, Maintenance and Repair) plans through Risk Based Inspection (RBI) methods [4–6]. The assessment of PoD and PFA is even deduced from inter-calibration of NDT tools [7–9] or from the modeling of the noise and the signal. The second approach will be presented in this paper. Due to the significant economic interest and cost (both direct and indirect) and the availability of original data, steel harbor structures are of particular interest.

First, on the basis of several previous works, this paper reviews the theoretical aspects generating from detection theory and probabilistic modeling of inspections results. The objective is to provide inputs in the computation of mathematical expectation of RBI cost models. The paper then introduces the concept of receiver operating characteristics (ROC) curves. A parametric modeling is suggested to assess the effect of the shape of ROC curves on the decision process: the polar coordinates of NDT-BPP (Best Performance Point) for characterizing ROC curves. The definition of the two parameters of the  $\alpha\delta$  method is reminded for comparing ROC curves of NDT-tools by a simple and tractable way.

The third part is devoted to the main principles of optimization through RBI methods, probabilistic performance of NDT tools being known. Bayesian modeling of inspection results is considered for the probabilistic modeling of hazards involved in the decision scheme. This allows us to reach to a decision from real defect through NDT measure. It is illustrated with a current definition of costs involved in the risk analysis.

Finally, this paper focuses on two applications lying on the  $\alpha\delta$  method. First, several strategies of NDT tool improvements within a fixed budget are compared from a risk point of view. Several protocols of inspection of

harbors steel structures are compared in this RBI context and the effects on risk assessment of an improvement of a protocol on the extra-costs are analyzed.

## 2 Probabilistic modeling of inspection based on detection theory

### 2.1 Probability of detection and probability of false alarm

The most common concept, which characterizes the uncertain performance of inspection tools, is the PoD. Let  $a_d$  be the minimal defect size, called detection threshold, under which it is assumed that no detection is possible. PoD is defined as (Eq. (1)):

$$\text{PoD} = P(\hat{D} \geq a_d) \quad (1)$$

where  $\hat{D}$  is the variable that represents the measured defect size  $\hat{d}$ , the real defect size (i.e. the real signal without noise) being  $D$ .

Assuming that we know the probability density functions of noise and signal amplitude, after fitting empirical distribution for instance, PoD and PFA have the following expression (Eqs. (2) and (3)):

$$\text{PoD} = \int_{a_d}^{+\infty} f_{\text{signal+noise}}(\hat{d}) \partial \hat{d} \quad (2)$$

$$\text{PFA} = \int_{a_d}^{+\infty} f_{\text{noise}}(\eta) \partial \eta \quad (3)$$

where  $\hat{d}$  is the measured defect size (response level of NDT tool i.e. “signal + noise”),  $\eta$  the noise,  $f_{\text{signal+noise}}$  and  $f_{\text{noise}}$  are respectively the probability density functions of “signal + noise” of  $\hat{D}$  and “noise”  $\Lambda$ , the random variable of  $\eta$ . Here noise  $\Lambda$  and signal  $D$  are considered as independent random variables.

Thus, PoD is a function of the detection threshold, the measured defect size and the noise while PFA depends on the detection threshold and noise only [10]. Noise is dependent on the decision-chain “physical measurement to decision on defect measurement”, the harsh environment of inspection and the complexity of testing procedure (the link between the diver and the inspector for underwater inspections for instance).

Figure 1 illustrates the PDF (Probability Density Function) and the area to be computed for the evaluation of (1-PoD), hence PoD, and PFA for a given detection threshold in the case where “signal + noise” and “noise” are normally distributed.

### 2.2 Receiver operating characteristic (ROC) curve

For a given detection threshold, the pair (PFA, PoD) defines NDT performance. This pair can be considered as coordinates of a point in  $R^2$  (square integrable space of

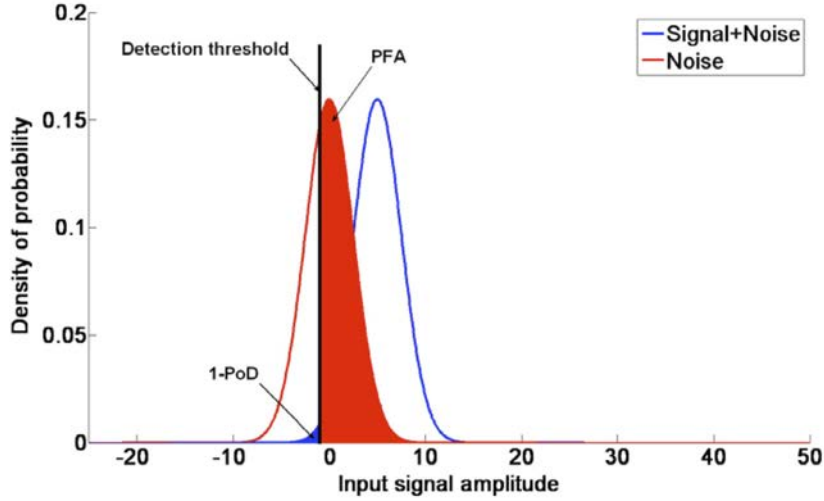


Fig. 1. Illustration of PoD and PFA (signal + noise and noise normally distributed) for detection threshold  $a_{d1}$ .

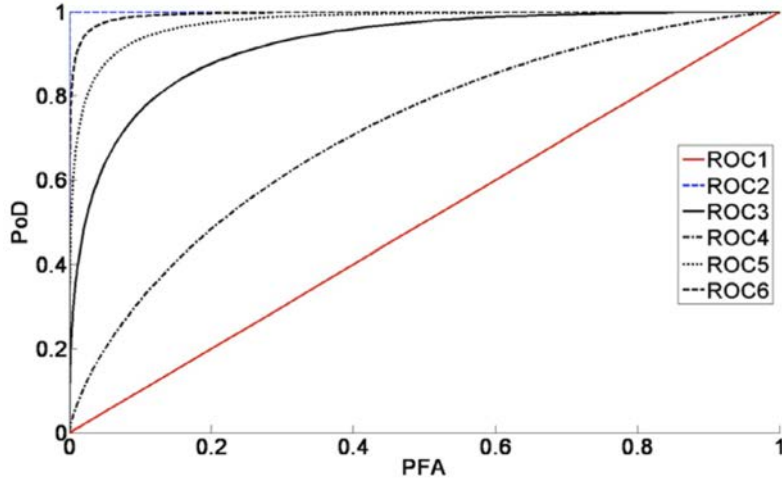


Fig. 2. Example of ROC curves for several NDT performance.

real numbers) with axes representing PFA and PoD. Let us consider that  $a_d$  takes values in the range  $]-\infty; +\infty[$ . These points belong to a curve called Receiver Operating Characteristic (ROC) which is a parametric curve with parameter  $a_d$  and defined by equations (2) and (3).

An example of ROC curve (ROC 3) is plotted in figure 2 and computed using the PDF presented in figure 1 corresponding to normal distributions.

The ROC curve is a fundamental characteristic of the NDT tool performance for a given defect size. Perfect tool is represented by a ROC curve reduced to a single point whose coordinates are:  $(\text{PFA}, \text{PoD}) = [0, 1]$ . The ROC curve represents a NDT tool performance facing a given PDF of a defect or a defect range. More details are available in [1].

Figure 2 presents six theoretical ROC curves, each one corresponding to a different NDT tool performance. The worst curve is ROC 1, meaning that some noise can be easily detected even if there is no defect. This leads to a high number of false alarms. As a result, overall

performances are poor. In contrast, the best plotted ROC curve is ROC 2, which differs considerably with the previous curve. The PoD reaches very quickly values near unity, with very small PFA for high values of PoD: this curve appears as coincident with y-axis and the horizontal line “PoD = 1”. Overall performances are very good. These ROC curves can be obtained even by considering two techniques and the same defect range, or one technique and two defect ranges, or one technique applied in various conditions (even if the testing procedure is rigorously followed during inspection). This is the case for underwater inspections of marine/coastal structures where accessibility and visibility are limited and conditions for the use of NDT tools are not optimal.

### 2.3 The $\alpha\delta$ method

A simple geometric characterization of ROC curves is the distance between the curve and the best performance point (BPP) of coordinates  $(\text{PFA} = 0, \text{PoD} = 1)$  [11]. By

definition, the bigger the distance, the worse is the performance. The point on the ROC curve corresponding to the lowest distance between BPP and the curve is called the performance point of the NDT tool (NDT-BPP). As the configurations of ROC curves for the same distance are various, this paper considers a curve characterization by using the polar coordinates of the NDT-BPP (see [11]). The NDT-BPP polar coordinates are defined by:

- the radius  $\delta_{\text{NDT}}$  equals the performance index (NDT-PI) (distance between the best performance point and the ROC curve);
- the  $\alpha_{\text{NDT}}$  is the angle between axis (PFA = 0) and the line (BPP, NDT-BPP).

Assessment of PoD and PFA from the knowledge of detection threshold can be directly deduced from intercalibration of NDT tools [7–9]. Generally these projects are expensive, and consequently, it is sometimes necessary to choose another approach. This article takes place in this context where inter-calibration is not available. Assessment of PFA and PoD thereby results from probabilistic modeling of the “noise” and “signal + noise” PDF as explained in the previous section.

### 3 Introduction of inspection in decision process

#### 3.1 Bayesian modeling of inspection results

To introduce inspections results in a RBI scheme, we model them through conditional probabilities. This format lies on Bayesian modeling and decision theory offers the theoretical basis [1, 12].

Four conditional probabilities are introduced:

- $P_1$ : probability there is no defect present, conditional to no defect detection;
- $P_2$ : probability there is no defect present, conditional to defect detection;
- $P_3$ : probability of the presence of defect, conditional to no defect detection;
- $P_4$ : probability of the presence of defect, conditional to defect detection.

In these definitions, the focus is on the presence or the absence of a defect after an inspection. After having been calculated, expressions of these probabilities as functions of PoD and PFA are deduced (see Eqs. (4)–(7)):

$$P_1 = \frac{(1 - \text{PFA})(1 - \gamma)}{(1 - \text{PoD})\gamma + (1 - \text{PFA})(1 - \gamma)} \quad (4)$$

$$P_2 = \frac{\text{PFA}(1 - \gamma)}{\text{PoD}\gamma + \text{PFA}(1 - \gamma)} \quad (5)$$

$$P_3 = \frac{(1 - \text{PoD})\gamma}{(1 - \text{PoD})\gamma + (1 - \text{PFA})(1 - \gamma)} \quad (6)$$

$$P_4 = \frac{\text{PoD}\gamma}{\text{PoD}\gamma + \text{PFA}(1 - \gamma)} \quad (7)$$

where  $\gamma$  is the probability of defect presence (see Eq. (8)):

$$P(X = 1) = \gamma; P(X = 0) = 1 - \gamma \quad (8)$$

In case of inspection of in-service structures, the presence of a defect is unknown. So  $\gamma$  is defined by expert judgment or predictive ageing laws. A sensitivity analysis is needed for a better understanding of the role of this parameter: It is carried out in [11].

When considering young structures, the low value of  $\gamma = 0.1$  can be understood as the probability of presence of large defects, and the high value of  $\gamma = 0.9$  as the probability of presence of small defects.

#### 3.2 Basic cost analysis

Optimization of inspection plans generally involves the minimization of a cost function. This cost function is a discrete random variable and the problem is usually formulated as the minimization of the total expected cost over a given period (Eq. (9)).

$$E(C) = \sum_i C(S_i)P(S_i) \quad (9)$$

where  $C(S_i)$  is the cost associated with the  $i$ th scenario  $S_i$  and  $P(S_i)$  is the probability that the  $i$ th scenario occurs.

In case of inspection, two cost functions can be considered. They are related to the cases of detection or no detection. The set of scenarios depends on the actions conditioned by the results of the inspection, termed maintenance policy in the following sections. For simplicity, the maintenance policy is:

- a “detection” leads to a repair;
- a “no detection” leads to a failure in case of presence of defect and to another inspection in case of absence of defect.

This last assumption considers that the probability of failure will reach unity in the future. It is assumed in this paper only because our present objective is not the optimization of inspection intervals and number of inspections. Under such circumstances, a single inspection campaign is performed during the whole lifetime.

The subsequent costs are denoted  $E(C)_d$  in the case of detection (Eq. (10)) and  $E(C)_{\text{nd}}$  in the case of no detection (Eq. (11)).

$$E(C)_d = C_4(1 - P_2) + C_2P_2 \quad (10)$$

$$E(C)_{\text{nd}} = C_1(1 - P_3) + C_3P_3 \quad (11)$$

where:

- $C_1$  is the cost associated to the event “no defects knowing that there are no detected defects”.  $C_1 = C_{\text{inspection}}$ ;
- $C_3$  is the extra cost associated to the event “defects knowing that there are no detected defects”.  $C_3 = C_{\text{inspection}} + C_{\text{failure}}$ ;

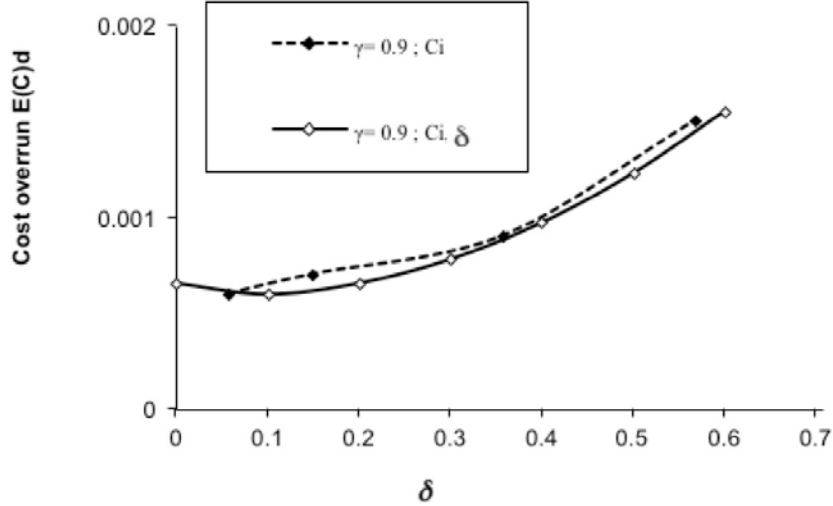


Fig. 3. Evolution of  $\overline{E(C)}_d$  with  $\delta$ .

- $C_4$  is the cost associated to the event “defects knowing that there are detected defects”.  $C_4 = C_{\text{inspection}} + C_{\text{repair}}$ ;
- $C_2$  is the extra cost associated to the event “no defects knowing that there are detected defects”.  $C_2 = C_{\text{inspection}} + C_{\text{repair}}$ . Due to the actions defined in the maintenance policy, it is here equal to  $C_4$ .

More complex cost models are described in [4].

## 4 Advanced cost analysis for ndt tool ranking

### 4.1 Cost model dependent of inspection performance

Let us now introduce the cost of inspection which depends on the NDT performance represented firstly only by  $\delta$  (see Sect. 2.3). For simplicity and to perform sensitivity studies, the cost can be written as a function of  $\delta$ :

$$C_{i,\delta} = (1 + \lambda_\delta)C_i \quad (12)$$

where  $\lambda_\delta$  is a decreasing function of  $\delta$ . The larger is  $\delta$  the worse is the technique and the lower is the cost. In the following, we select:  $\lambda_\delta = \frac{0.01}{\delta}$  for  $\delta \neq 0$ ;  $\lambda_0 = 1$ .

In the following, we focus on the cost overrun only and we state  $\gamma = 0.9$ . From equations (10)–(11), we consider only the following terms (Eqs. (13) and (14)):

$$\overline{E(C)}_d = C_2 P_2 \quad (13)$$

$$\overline{E(C)}_{\text{nd}} = C_3 P_3. \quad (14)$$

With these assumptions, it is shown that a minimum value of the cost overrun in case of detection  $\overline{E(C)}_d$  can be found (for  $\delta$  around 0.08) (white points in Fig. 3). By fixing  $C_i$  at a constant value (Tab. 1), the worse inspection performance ( $\delta$  tends to 0) has to be selected (full black pictograms in Fig. 3). Thus formalism allows for an optimal technique selection.

Table 1. Cost model selected for failure, repair, inspection.

	Cost
Failure	1.000
Repair	0.010
Inspection	0.001

### 4.2 Introduction of the $\alpha\delta$ method on cost assessment

In view to perform parametric studies and to compare inspection performances, two ratios are introduced (Eqs. (15) and (16)):

$$C_a = \frac{C_i}{C_r} = \text{Cost of inspection/ Cost of repair}; \quad (15)$$

$$C_b = \frac{C_r}{C_f} = \text{Cost of repair/ Cost of failure}. \quad (16)$$

A complete sensitivity study on  $\gamma$ , stakes, NDT-performance, NDT combinations is available in [11] based on [13] and it has been shown that the  $\alpha\delta$  method is powerful for NDT ranking.

Let us consider an updated expression of equation (12) depending both on  $\delta$  and  $\alpha$ . As the cost should decrease with  $\alpha$  (the lower is  $\alpha$  the better is the technique and the most expensive is the technique), we select:

$$\lambda_{\alpha,\delta} = \frac{0.01}{\sin(\alpha)\delta} \text{ for } \delta \neq 0 \text{ and } \alpha \neq 0; \lambda_{0,0} = 1. \quad (17)$$

Plots of function  $\lambda_{\alpha,\delta}$  for two strategies of improvement of a given NDT tool are drawn in figure 4. Here

- S1 is the variation of  $\delta$  from 0.5 to 0.2, and is represented by the top curve; and
- S3 is the variation of  $\alpha$  from  $30^\circ$  to  $60^\circ$  and is represented by the bottom curve.

This cost function will help us to quantify the interest of a NDT tool in terms of cost/benefit analysis.

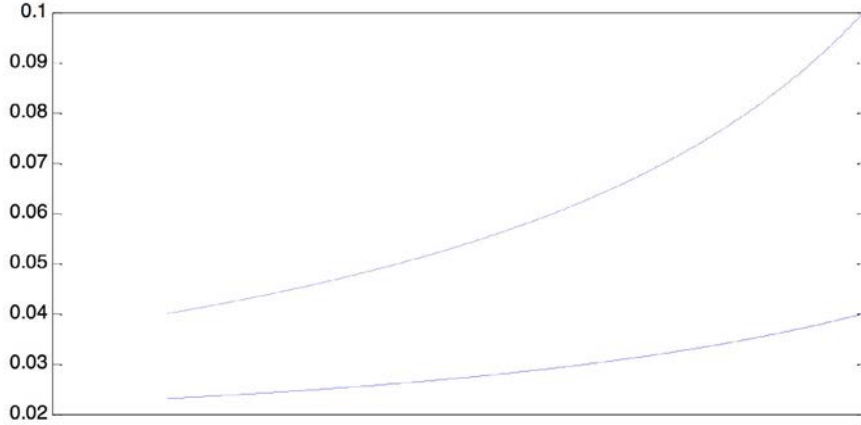


Fig. 4. Function  $\lambda_{\alpha,\delta}$  for S1 ( $\alpha$ -variation from 30 to 60, top curve) and S3 ( $\delta$ -variation from 0.5 to 0.2, bottom curve).

## 5 Applications to harbour structures

### 5.1 Theoretical study-case

First, for simplicity of analysis, let us focus on the comparison of NDT-tools with similar costs (Tab. 1) and on the extra costs in case of no detection ( $E(C)_{nd}$ ). Note that these costs are relative costs usually used to compare strategies [1]. Figure 5 presents levels of  $E(C)_{nd}$  according to the polar coordinates of NDT-BPP point ( $\delta_{NDT}$ ,  $\alpha_{NDT}$ ), for  $\gamma = 0.9$  and costs in Table 1. For this high probability of presence of defect ( $\gamma = 0.9$ ),  $E(C)_{nd}$  increases when  $\alpha_{NDT}$  decreases and  $\delta_{NDT}$  increases.

For a low probability of presence of defect ( $\gamma = 0.1$ ), other results have been obtained: extra costs of no detection  $E(C)_{nd}$  were maximum for values of  $\delta_{NDT}$  superior than 0.1 and for values of  $\alpha_{NDT}$  minor than  $30^\circ$ . When values of  $\alpha_{NDT}$  are higher than  $30^\circ$ ,  $E(C)_{nd}$  increases mainly as a function of  $\delta_{NDT}$ .

Let us consider NDT-BPP A in the following ( $\alpha = 30^\circ$ ,  $\delta = 0.5$ ) and the case  $\gamma = 0.9$ . Figures such as figure 5 allow us to compare inspection performances very quickly. If the performance is not sufficient, modifying the inspection protocol and increasing the formation of inspector or the NDT tool itself can improve it. If the cost of inspection is negligible in comparison to cost of repair (i.e.  $\lambda_{\alpha,\delta} \ll 10$ ) several strategies of improvement (reduction of risk) can be compared in terms of “displacement” of the original position A of the NDT-BPP on the same mapping (see positions of A', A'', and A''' in Fig. 5). If not, the cost expectation has to be reassessed.

Let us consider the effects of three strategies S1, S2 and S3 on NDT-BPP performance from a risk assessment point of view (here  $\overline{E(C)_{nd}}$ ):

- S1:  $\alpha$  remains at  $30^\circ$ ,  $\delta$  varies from 0.5 to 0.2: A moves to A';
- S2:  $\alpha$  varies from  $30^\circ$  to  $45^\circ$  and  $\delta$  varies from 0.5 to 0.35: A moves to A'';
- S3:  $\alpha$  varies from  $30^\circ$  to  $60^\circ$ ,  $\delta$  remains at 0.5: A moves to A'''.

We assume that each strategy needs the same budget B. In case of linearity of cost for instance, the cost in

$\alpha$ -direction is B/30 and B/0.3 in the  $\delta$ -direction. Figure 5 shows that the expectation of the cost  $\overline{E(C)_{nd}}$  is the lowest for the third strategy (0.67).

Following this criteria and the available budget, the improvement of NDT-tool should be along the  $\alpha$ -axis. This can be obviously extended to other strategies once the “target-point” in terms of coordinates  $\alpha$  and  $\delta$  is known.

### 5.2 Application on inspection of harbors steel structures

We now consider the inspection of sheet-piles in harbors by ultrasonic NDT tool, under uniform corrosion. This type of structure is one of the structures with high economical stakes in harbors. Thus, their maintenance is of great interest [10, 14]. The general procedure of inspection is described in [10] and depends on a grinding of the corroded surface, the calibration of the NDT tool, the checking of the communication quality between the diver and the to-side operator and the recurrent measure to control the bias. Depending on the choices made at each step, several protocols have been developed. Within the French project GEROM [14] and the European projects Medachs (<http://www.medachs.u-bordeaux1.fr>) and Duratinet (<http://www.duratinet.org>), three types of practical protocols have been identified which correspond to the progressive improvement of the procedure. The first one (protocol P1) is the most recent and the most rigorous and the third one (Protocol P3) was initially developed with a low quality control. To model these protocols, we have analyzed the standard deviation of the noise from a database of about 35 000 measurements. Each measure was repeated three times at the same location, the mean was considered, after analysis of the protocol and expert judgment, as the real value and the noise was defined as the difference between each measure at this location and the real value:

- Protocol 3 (P3) consists in a simple brushing of corrosion products before ultrasonic measurements. Then it is shown that the standard deviation depends on



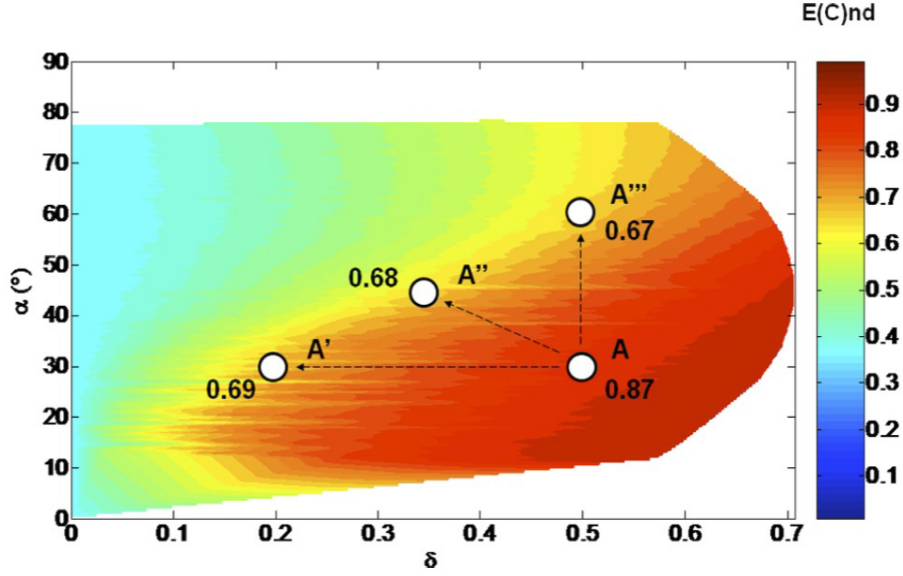


Fig. 5. Mapping of extra cost in case of no detection  $\overline{E(C)_{nd}}$  in polar plane for  $\gamma = 0.9$ .

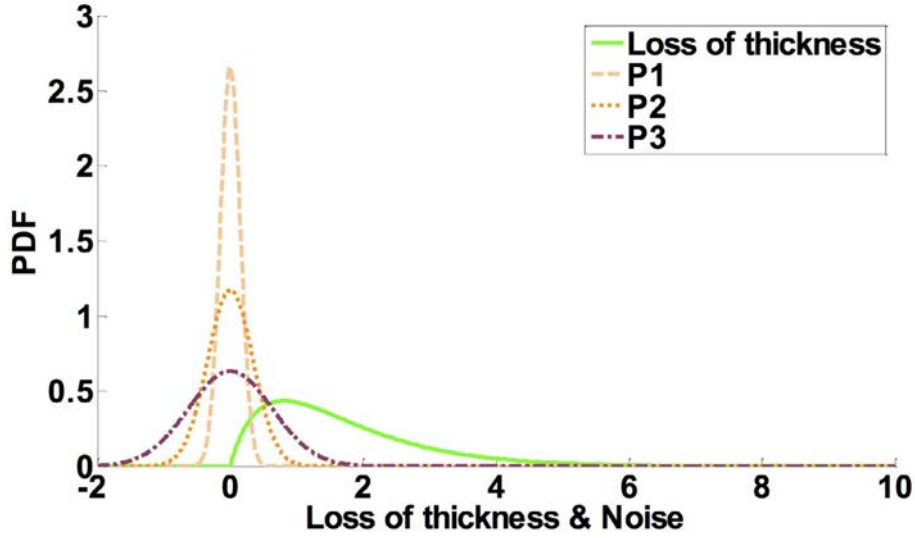


Fig. 6. Distribution of the noise for three protocols and of the corrosion (mud zone after 25 years).

the measurement, i.e. the loss of steel  $\mu_c$ , following equation (18).

$$\sigma_{\eta, P_3} \approx 0.29 \mu_c + 0.15 \text{ (mm)}. \quad (18)$$

- Protocol 2 (P2) is similar to the previous one but grinding replaces brushing and a medium quality control is applied after ultrasonic measurement and in the data base. The standard deviation of the noise varies from 0.15 mm to 0.65 mm depending on the time allocated to the quality control. Two assumptions are considered in this paper:

- (a) the control is of medium quality and;
- (b) the control is of bad quality.

Standard deviations are respectively:  $\sigma_{\eta, P_{2,a}} \approx 0.35 \text{ (mm)}$ ;  $\sigma_{\eta, P_{2,b}} \approx 0.65 \text{ (mm)}$ .

- Protocol 1 (P1) corresponds to grinding of corrosion products and a rigorous quality control that leads to very fair standard deviation of the noise (0.15 mm), whatever the position of the diver and the level of corrosion:  $\sigma_{\eta, P_1} \approx 0.15 \text{ (mm)}$ .

In this application, we assume the noise to be normally distributed. Other models based on polynomial chaos [10] can be fitted but it doesn't change the results of the present application. The PDF of noise for each protocol are plotted in figure 6 with the distribution of corrosion (here the signal) in the mud zone after 25 years obtained from the model of long term corrosion of Boero [15].

In that case, ROC curves obtained for (P1), (P2a) and (P3) are plotted in figure 7.

Let first consider that costs of each protocol are similar. We analyse the position of each protocol in the  $\alpha\delta$



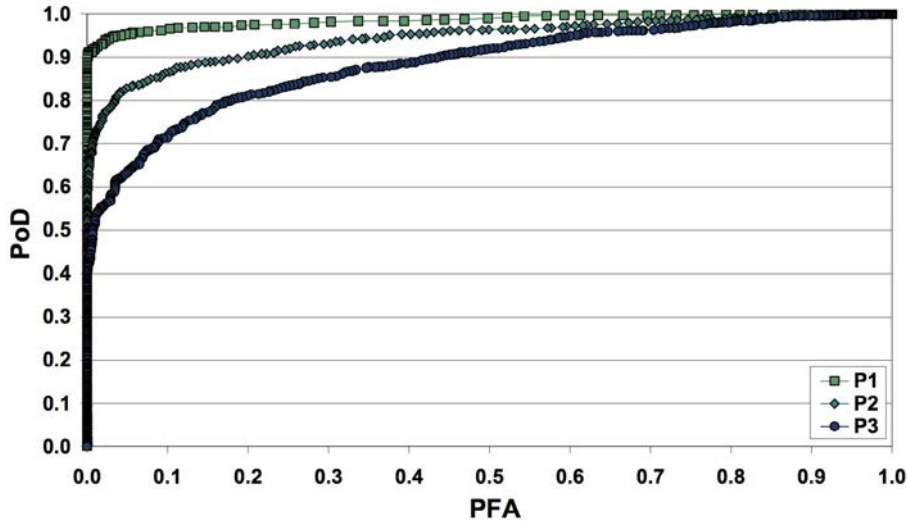


Fig. 7. R.O.C curves for the three protocols P1, P2a and P3.

plane with a focus on the extra-cost in case of no detection  $\overline{E(C)}_{nd}$  and  $\gamma = 0.9$ . Due to the analytical expression of  $\sigma_{\eta, P_3}$ , the level of corrosion will affect the noise. Therefore we analyse the effect of the increase of corrosion with time from the model of Boero [15] at three times (10, 25 and 50 years) and in two areas: the low level of tide where the corrosion is maximum and the mud area where it is minimum. The PDF are plotted in Figure 8. It is seen that the Gamma PDF selected in this model is consequent with expert judgment: initially, there is no-corrosion and loss of thickness follows a Dirac distribution at  $x = 0$  and progressively it becomes exponential as illustrated at 25 years in the lower tidal area ( $z_{L25}$ ) and finally has a very low probability of no corrosion at 50 years (early at 10 years in the mud zone where the corrosion is faster).

Figures 9 to 11 present the mapping of  $\overline{E(C)}_{nd}$  with  $\gamma = 0.9$  for the costs in Table 1 respectively after 10, 25 and 50 years with the position of each protocol in each zone of measurement.

Several comments can be highlighted from these results:

- after 10 years (Fig. 9), in the mud zone, the over-cost in case of non detection is larger than in the tidal zone. It is due to the fact that the corrosion is smaller and the noise affects strongly the decision. In both areas, only the protocol (P1) can be distinguished with a significant improvement of the over-cost;
- after 25 years (Fig. 10), all the protocols progress because the corrosion is larger then easier to detect. Results are very good with protocol (P1) both in tidal and mud areas and protocol (P2a) leads to similar results but only in the tidal area where the corrosion is larger. In other cases, we can note that protocol (P3) is quite good in the tidal area and that (P2b) is the worst whatever the inspected area;
- after 50 years (Fig. 11), protocols (P1) and (P2a) leads to similar results whatever the inspected zone and

Table 2. Cost model selected for failure, repair, practices of inspection.

	Cost
Failure	1.0000
Repair	0.0100
Inspection – Practice 1 (P1)	0.0025
Inspection – Practice 2 (P2a)	0.0020
Inspection – Practice 3 (P3)	0.0010

protocol (P3) is now acceptable too. Only protocol (P2b) leads to medium results (significant overcost).

It is interesting to see here that the effect of the protocol depends on the corrosion level thus on the time and the inspected area.

The cost of each protocol and the role of the probability of corrosion presence  $\gamma$  is considered next. Due to the duration of the procedure and the material implemented, practice (P3) is the cheapest and practice (P1) the most expensive. For protocol (P2) only (P2a) model is considered. Updated costs are given in Table 2.

The signal is here the distribution of the loss of steel for corrosion in the mud zone after 25 years: thus,  $\mu_c = 1.68$  mm and  $\sigma_{\eta, p_3} \approx 0.64$  (mm).

Table 3 presents the results for  $\overline{E(C)}_d$  and  $\overline{E(C)}_{nd}$  for three values of  $\gamma$  and the three protocols (P1), (P2a) and (P3). It is shown that protocol (P1) leads to the lowest costs whatever the level of  $\gamma$ .

The discrepancies between (P1), (P2a) and (P3) are higher for  $\gamma = 0.1$  and  $\gamma = 0.9$ . For  $\gamma = 0.5$ , it appears that the protocols lead to very similar costs. Thus, the knowledge of the probability of defect presence  $\gamma$  is a major input for a risk-based selection of NDT-protocol.

## 6 Conclusion

Concepts of ROC curves coming from detection theory are very useful in order to quantify the performance of

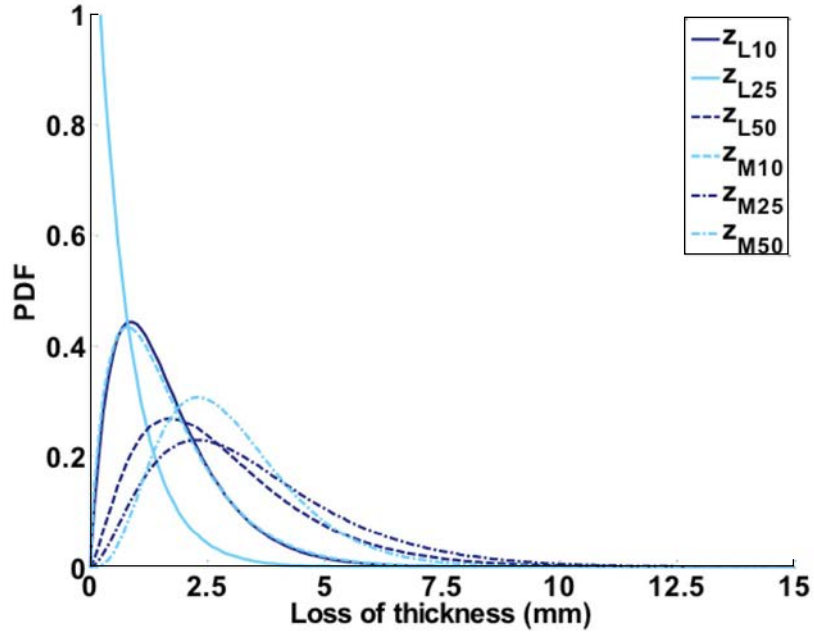


Fig. 8. PDF of thickness loss in the mud (M) and lower tidal (L) zones after 10, 25 and 50 years.

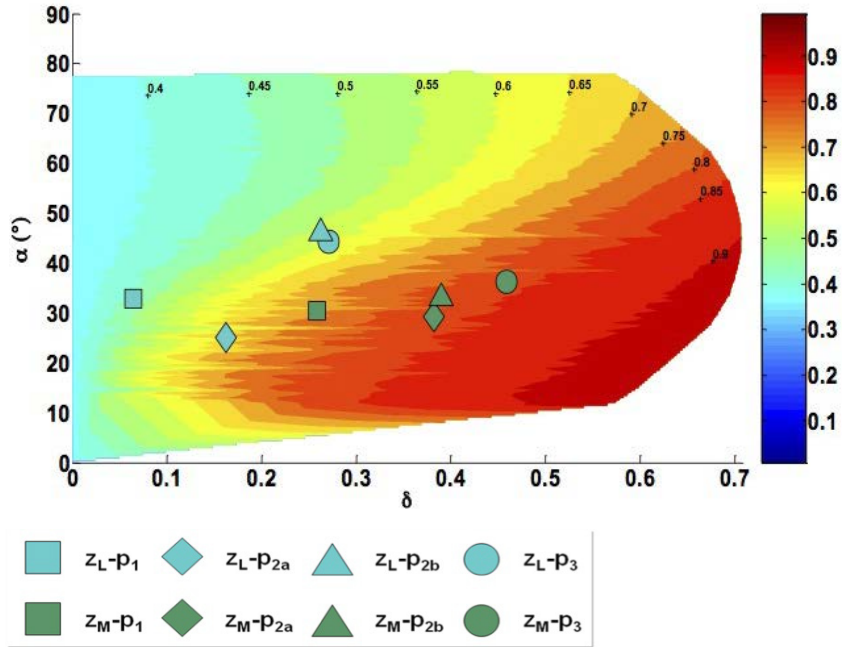
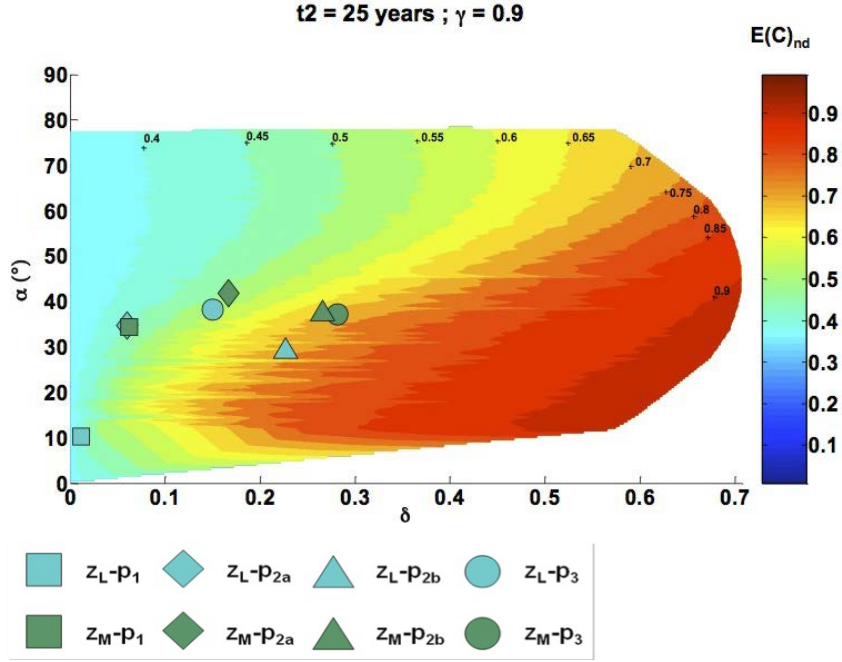


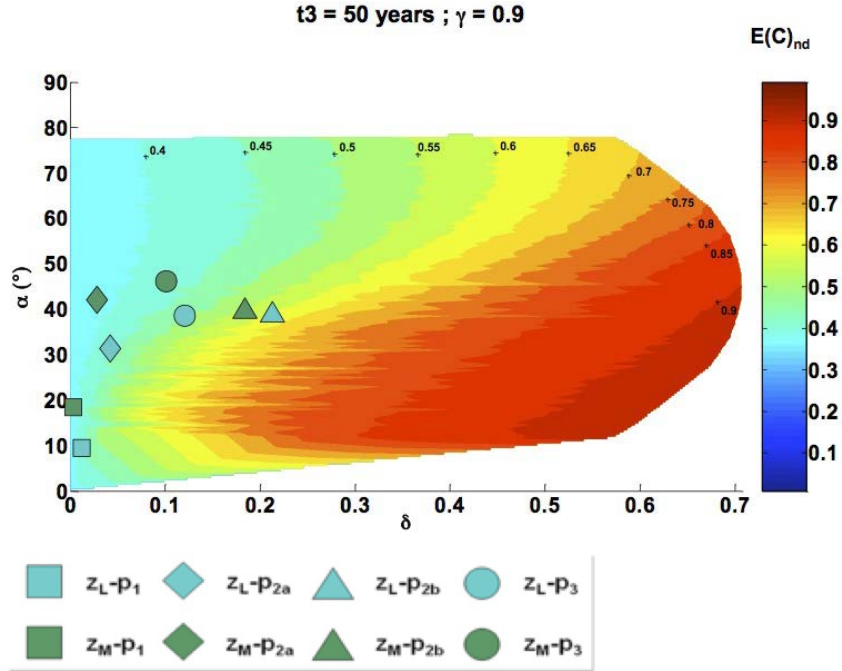
Fig. 9. Mapping of extra cost in case of no detection  $\overline{E(C)}_{nd}$  in polar plane for  $\gamma = 0.9$  after 10 years of corrosion and position of each protocol in mud ( $Z_M$ ) and lower tide ( $Z_L$ ) areas.

Table 3. Performances of the three practices of inspection based on cost analysis.

	$\gamma = 0.1$		$\gamma = 0.5$		$\gamma = 0.9$	
	$\overline{E(C)}_d$	$\overline{E(C)}_{nd}$	$\overline{E(C)}_d$	$\overline{E(C)}_{nd}$	$\overline{E(C)}_d$	$\overline{E(C)}_{nd}$
Practice 1 (P1)	0.0049	0.0279	0.0020	0.1678	0.0003	0.4506
Practice 2 (P2)	0.0052	0.0324	0.0021	0.2016	0.0004	0.5878
Practice 3 (P3)	0.0056	0.0378	0.0022	0.2373	0.0004	0.6679



**Fig. 10.** Mapping of extra cost in case of no detection  $\overline{E(C)}_{nd}$  in polar plane for  $\gamma = 0.9$  after 25 years of corrosion and position of each protocol in mud ( $Z_M$ ) and lower tide ( $Z_L$ ) areas.



**Fig. 11.** Mapping of extra cost in case of no detection  $\overline{E(C)}_{nd}$  in polar plane for  $\gamma = 0.9$  after 50 years of corrosion and position of each protocol in mud ( $Z_M$ ) and lower tide ( $Z_L$ ) areas.

Non-Destructive-Techniques. This paper reviews the theoretical aspects coming from detection theory and probabilistic modeling of inspections results with the view to provide inputs in the computation of mathematical expectation of RBI cost models.

The effect of the shape of ROC curves on the extra costs is introduced through the  $\alpha\delta$  method. It is shown

how to use the two polar coordinates  $\delta_{NDT}$  and  $\alpha_{NDT}$  of the NDT Best Performance Point in the plane (PFA, PoD) in view to compare the Risk Based performance of NDT tools or to improve a given NDT tool. The expectation of the extra cost in the case non detection  $\overline{E(C)}_{nd}$  is selected for illustration. A usual scale of costs for inspection, repair and failure is introduced for the illustration.

The paper applied this method to illustrate two objectives:

- The improvement of a NDT-tool, within similar costs, in view to decrease the extra costs. This is shown that the mapping of overall-costs allows us to analyze the effect of NDT-tool improvement from risk point of view.
- The selection of a protocol among several candidates with related costs. The computing of extra-costs is shown to be dependent of the initial knowledge of the defect presence through the probability of defect presence  $\gamma$ . This part of the paper is illustrated through the inspection of steel harbor structures submitted to uniform corrosion.

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