



Kennisprogramma Natte Kunstwerken  
*Kennisplan 2024*

*Vervangings- en renovatieopgave  
natte kunstwerken in Nederland*

Kennisbijdrage:

## **Einde levensduur damwanden**

Evaluation of the measurement uncertainty of  
Pulsed Eddy Current Testing (PECT) for  
measuring the residual thickness of sheet pile  
walls

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# Voorwoord

## Kennisprogramma Natte Kunstwerken

Sluizen, stuwen, gemalen en stormvloedkeringen zijn belangrijke assets waarvoor beheerders zoals Rijkswaterstaat en de waterschappen verantwoordelijk zijn. Veel van deze natte kunstwerken in de waterinfrastructuur bereiken de komende decennia het einde van hun (technische en/of functionele) levensduur. Zij kunnen daardoor hun functies naar verwachting niet meer adequaat blijven uitoefenen. Dit zal ten koste gaan van de mate waarin de waterinfrastructuur voldoet aan betrouwbaarheidseisen. In het kader van goed assetmanagement staan we dan ook voor de enorme opgave om deze kunstwerken te vervangen of te renoveren. Welke kennis hebben we nodig om dat efficiënt, kostenbesparend en toekomst-bestendig aan te pakken?

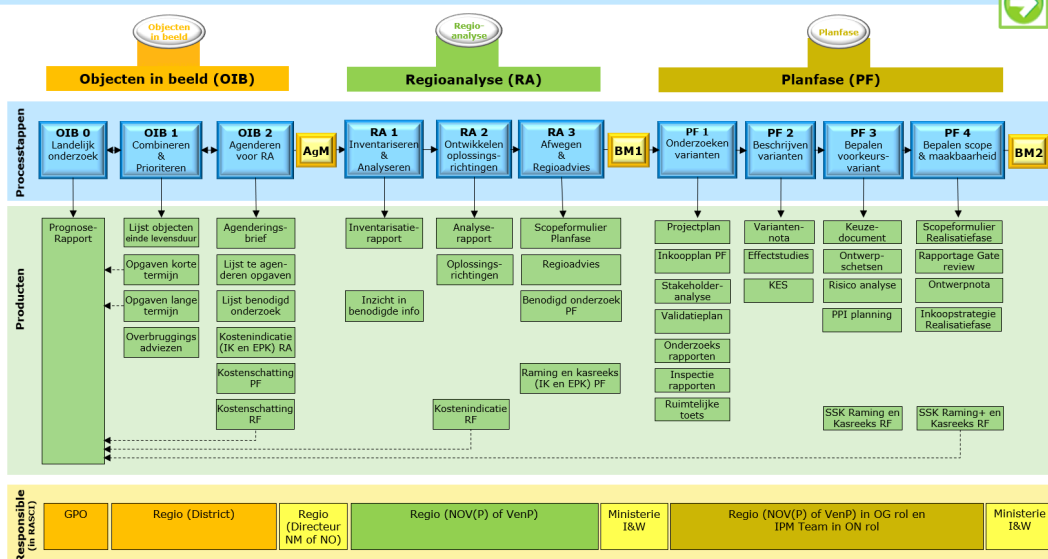


In het Kennisprogramma Natte Kunstwerken (KpNK) ontwikkelen en bundelen Deltares, MARIN, Rijkswaterstaat en TNO deze kennis op basis van de Samenwerkingsovereenkomst Natte Kunstwerken.

## Werkwijze vervangings- en renovatieproces

De laatste jaren richten we ons niet meer uitsluitend op een-op-een vervanging van kunstwerken. We zoeken steeds meer naar mogelijkheden om hun levensduur te verlengen en (noodzakelijke) ingrepen te koppelen aan gebieds- en netwerkontwikkelingen en aan functionele ontwikkelingen. Rijkswaterstaat heeft als assetmanager een vernieuwde werkwijze voor dit vervangings- en renovatieproces (VenR) opgesteld om een uniform en systematisch proces te hebben waarmee een VenR-maatregel transparant onderbouwd kan worden (zie Figuur 1).

### Procesketen VenR (tot aan Realisatie)



Figuur 1: Procesketen VenR binnen Rijkswaterstaat

Samenvatting 'Evaluation of the measurement uncertainty of Pulsed Eddy Current Testing (PECT) for measuring the residual thickness of sheet pile walls' (kennisbijdrage vanuit werkpakket 'Einde levensduur damwanden') – DEF20260624

Deze procesketen vormt de basis waar de kennisontwikkeling van het kennisprogramma aan bijdraagt.

### **Twee-stappen-benadering en drie kernvragen**

De kennis die we ontwikkelen binnen het Kennisprogramma Natte Kunstwerken draagt bij aan de stapsgewijze-benadering binnen deze Procesketen VenR:

- stap 1 (*Objecten in Beeld*): richt zicht op (het einde van) de technische levensduur van een kunstwerk en het agenderen van de VenR-opgave in het *Prognoserapport*;
- stap 2 (*Regioanalyse*): brengt vooral de relatie in kaart tussen het kunstwerk en de netwerken waar het (samen met andere kunstwerken) deel van uitmaakt. In het resulterende *Regioadvies* gaat het ook over (het einde van) de functionele levensduur.

Inhoudelijk vindt het onderzoek plaats aan de hand drie *kernvragen*:

1. Hoe lang gaat mijn kunstwerk nog mee, zowel technisch als functioneel?
2. Welke alternatieven heb ik, behalve een-op-een vervanging?
3. Hoe weeg ik de alternatieven tegen elkaar af?

### **Programmaplan, jaarlijkse kennisplannen en samenwerking**

Het programmaplan omvat de achtergronden en ambities voor de gehele looptijd van het Kennisprogramma Natte Kunstwerken. Jaarlijks worden deze ambities uitgewerkt in een kennisplan en een bijbehorend financieringsplan. Andere partijen, zoals waterschappen, adviesbureaus en andere (commerciële) organisaties, nodigen we uitdrukkelijk uit om deel te nemen aan het gezamenlijk uitvoeren van een kennisplan, bijvoorbeeld met kennisbijdragen in voor hen relevante onderzoeksprojecten, met praktijkervaringen of financiële bijdragen.

### **Resultaten delen**

Bijdragen en onderzoeksresultaten uit ons Kennisprogramma Natte Kunstwerken delen we met de hele sector via onze website ([www.nattekunstwerkenvandetoekomst.nl](http://www.nattekunstwerkenvandetoekomst.nl)) en op andere manieren.

Hieronder vindt u een kennisbijdrage binnen werkpakket 'Einde levensduur overige HWS-objecten' uit het Kennisplan 2024. Het omvat eerst de samenvatting van het onderzoek 'Degradation of concrete structures in marine environments'. Deze activiteit is namens het Kennisprogramma Natte Kunstwerken geleid door TNO. Na de samenvatting vindt u het volledige onderzoeksverslag in de vorm van een onderzoeksrapport.

N.B. Het volledige onderzoeksrapport is gelijk aan het originele onderzoeksrapport van TNO, met uitzondering van het titelblad en de technische samenvatting. Bij publicatie van dit onderzoeksverslag op de KpNK-website is het titelblad om privacyredenen verwijderd. En een meer toegankelijke samenvatting volgt hierna.

## Meer informatie

- Het Kennisprogramma Natte Kunstwerken is de uitwerking van de onderzoekslijn 'Toekomstbestendige Natte Kunstwerken' binnen het Nationaal Kennisplatform voor Water en Klimaat (NKWK). Zie [www.waterenklimaat.nl](http://www.waterenklimaat.nl)

**NKWK**

- Voor meer informatie over het programma Kennisprogramma Natte Kunstwerken, zie [www.nattekunstwerkenvandetoekomst.nl](http://www.nattekunstwerkenvandetoekomst.nl).



- Voor vragen over het Kennisprogramma Natte Kunstwerken en het kennisplan 2024 kunt u terecht bij Martine Brinkhuis, email [martine.brinkhuis@rws.nl](mailto:martine.brinkhuis@rws.nl)
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## Samenvatting

# Einde levensduur damwanden

## Evaluation of the measurement uncertainty of Pulsed Eddy Current Testing (PECT) for measuring the residual thickness of sheet pile walls

Hieronder vindt u een kennisbijdrage van het werkpakket 'Einde levensduur damwanden' uit het Kennisplan 2024. De focus van dit werkpakket ligt op de betrouwbaarheidsbeoordeling van bestaande damwandconstructies, op degradatie en op duurzaamheid van stalen damwanden.

Deze samenvatting gaat over het onderzoek naar kennisontwikkeling rondom de meetonzekerheid van een niet-traditionele meettechniek (PECT) die gebruikt wordt voor de inspectie van stalen damwanden. Deze kennis is ondersteunend bij het beoordelen van de conditie en betrouwbaarheid van stalen damwandconstructies, wat de basis vormt voor vervangings- en renovatiebeslissingen van damwanden.

### Aanleiding en probleemstelling

De damwanden die geplaatst zijn in de jaren 50, 60 en 70 van de vorige eeuw zijn door de jaren heen aangetast door corrosie. Corrosie vermindert de wanddikte van de stalen damwandplanken, waardoor de betrouwbaarheid van de constructie afneemt. Om de technische restlevensduur scherp en efficiënt te bepalen zijn nauwkeurige metingen van de restdikte cruciaal. Tegenwoordig wordt de inspectie van stalen damwanden uitgevoerd met ultrasone techniek. Hiervoor geeft het CROW-protocol "Protocol gemiddelde staaldiktebepaling van 6 aangrenzende stalen damwandplanken met ultrasone metingen" aan beheerders en inspectiebedrijven richtlijnen en advies voor het aantal te inspecteren damwandprofielen en de locatie van de meetpunten.

Het stalen oppervlak moet echter gereinigd worden om nauwkeurige ultrasone metingen te verkrijgen, in het bijzonder onder water, waar de meest kritieke doorsneden van verankerde damwanden zich bevinden. In de offshore sector wordt Pulsed Eddy Current Testing (PECT) veel gebruikt voor onderwaterinspecties omdat deze meettechniek geen contact met het staaloppervlak vereist en de staaldikte kan meten door mariene groei, corrosieproducten en beschermende coatings heen. Dit maakt het mogelijk om damwanden te inspecteren zonder duikers, waardoor de inspecties mogelijk efficiënter en veiliger kunnen plaatsvinden.

Aangezien deze meettechniek echter niet de state-of-practice is voor de inspectie van stalen damwanden, dient de meetonzekerheid te worden onderzocht.

### Onderzoeksvragen (WAT)

Wat is de meetonzekerheid van Pulsed Eddy Current Testing (PECT) voor het meten van de restdikte van damwandplanken? Hoe verhouden PECT-metingen zich tot de state-of-practice van ultrasone metingen?

### Onderzoeksaanpak en -methode (HOE)

Dit onderzoek naar de meetonzekerheid van PECT-metingen bestaat uit twee fases. In de eerste fase werd de restdikte van een groep van 67 jaar oude damwandplanken uit de Roggebotsluis onderzocht. PECT-metingen werden eerst in situ uitgevoerd door de inspectiebedrijven SGS en RPS. Daarna werden

de PECT-metingen herhaald in het TNO-Bouwinnovatie Lab in Delft, aangevuld met lasermetingen en ultrasone metingen door TNO. In de tweede fase, werden de meetfouten van PECT bepaald op basis van de vergelijking tussen de PECT-metingen (in situ en in het laboratorium) en de lasermetingen. Daarnaast werden de PECT-metingen ook met de state-of-practice ultrasone metingen vergeleken. Op basis van de analyse van de meetfouten van PECT werd de meetonzekerheid beschreven in probabilistische termen.

### **Onderzoeksresultaten en synthese**

Uit dit onderzoek kunnen de volgende conclusies worden getrokken:

- de externe omstandigheden tijdens de metingen (in situ vs. laboratoriumomstandigheden) kunnen de nauwkeurigheid van PECT-metingen aanzienlijk beïnvloeden;
- de overgrote meerderheid van de PECT-meetfouten is niet groter dan  $\pm 1,5$  mm, maar sommige fouten kunnen significant en aan de onveilige kant zijn (overschatting van de restdikte);
- de PECT-metingen zijn niet minder betrouwbaar dan de ultrasone metingen onder laboratoriumomstandigheden;
- het effect van meetfouten op het weerstandsmoment van de damwandconstructie bleek beperkt te zijn voor de beschouwde damwandprofielen.

PECT biedt de mogelijkheid damwanden te inspecteren zonder het gebruik van duikers, wat mogelijk leidt tot efficiëntere en veiligere inspecties.

Het onderzoeksrapport volgt direct achter deze samenvatting.

### **Evaluatie en vooruitblik**

Om de PECT-meettechniek systematisch en verantwoord in de praktijk te kunnen gebruiken voor de inspectie van bestaande damwandconstructies, is het nodig om eisen en aanbevelingen vast te stellen in een meetprotocol voor PECT. Het effect van externe in situ omstandigheden op de nauwkeurigheid van de metingen, kan namelijk aanzienlijk zijn. Een meetprotocol kan helpen deze effecten te beperken. PECT biedt de mogelijkheid damwanden te inspecteren zonder het gebruik van duikers, wat mogelijk leidt tot efficiëntere en veiligere inspecties.

# **Evaluation of the measurement uncertainty of Pulsed Eddy Current Testing (PECT) for measuring the residual thickness of sheet pile walls**

TNO 2025 R10763 – 30 July 2025  
Evaluation of the measurement uncertainty of  
Pulsed Eddy Current Testing (PECT) for  
measuring the residual thickness of sheet pile  
walls

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# 1 Introduction

The risk management framework for existing infrastructural assets relies on multifaceted information sources, one of which is the current condition of the structure. Specifically, for sheet pile walls, thickness reduction due to corrosion emerges as the principal factor compromising safety after prolonged exposure periods. Thus, acquiring accurate data on the residual thickness of the steel profiles and the corrosion rates becomes crucial for informed decision-making concerning the repair, replacement, or life extension of these assets. Given the significance of corrosion as the predominant degradation mechanism affecting sheet pile walls, TNO has engaged in research under the Kennisprogramma Natte Kunstwerken (KpNK) initiative. This research focuses on the methodologies for measuring the residual thickness of sheet pile profiles and the analytical interpretation of such measurements to evaluate the remaining service life of the assets.

Currently, inspections of sheet-pile walls are performed by using the ultrasound measurement technique. The number of sheet pile profiles to be inspected and the location of the measurement points are given in the CROW “Protocol gemiddelde staaldiktebepaling van 6 aangrenzende stalen damwandplanken met ultrasone metingen” [1].

The issue of safety of the divers during inspections raised serious concerns about the use of the ultrasound technique underwater. An alternative to this inspection technique is Pulsed Eddy Current Testing (PECT), which is widely used in other domains (e.g. offshore). The main advantage of PECT is that the presence of corrosion products or other types of irregularity of the surface hardly affect the accuracy of the measurements. Thus, no divers would be required for inspecting sheet pile structures.

Aiming to take a well-informed decision about the replacement of the ultrasound technique with the PECT, Rijkswaterstaat asked TNO to carry out a comparison between these two techniques on several sheet-pile profiles taken from the Roggebot lock.

## 1.1 Objective

The objectives of this research project are:

- ) to assess the measurement uncertainty of PECT in measuring of the residual thickness of sheet pile profiles
- ) to compare PECT and ultrasonic technique in terms of measurement accuracy.

## 1.2 Approach

The measurement uncertainty of PECT is herein defined as the difference between reference measurements of the residual thickness and those obtained via the PECT at the same measurement points. For this purpose, 12 sheet pile profiles pulled out in 2023 from the Roggebot lock have been used in this study.

The reference measurements are laser measurements performed at the TNO laboratory in Delft. The PECT measurements were performed in situ and at the TNO laboratory in Delft by two inspection companies, SGS and RPS. The purpose of this double set of measurements was to assess the accuracy of the PECT measurements under the operational conditions to be expected during the inspection and in the best possible conditions, such as in the laboratory. Since PECT is not a state-of-the-art technique for sheet pile walls, the assessment of the

measurement uncertainty of PECT has been complemented with the comparison with the ultrasound measurement technique.

To summarize, the following distinct datasets of measurements have been collected as part of this investigation:

- › Laser measurements in the laboratory setting, conducted by TNO.
- › PECT measurements in situ, conducted by SGS and RPS.
- › PECT measurements in the laboratory setting, conducted by SGS and RPS.
- › Ultrasound measurements in the laboratory setting, conducted by TNO.

## 1.3 Scope and limitations

The measurement uncertainty of PECT is investigated in this study based on measurements of the residual thickness of sheet pile walls performed in-situ and in laboratory conditions. The extrapolation of the results of the investigation to other retaining structures, such as combi-walls, should be performed with extreme care. Furthermore, only two inspection companies took part to the measurement campaign. Therefore, the measurement uncertainty estimated in this study may not be representative of the future practice.

## 1.4 Reading guide

The remainder of this report is organised as follows. In chapter 2, the datasets of measurements of the residual thickness are presented. Chapter 3 concerns the identification of the corrosion zones in the direction of the depth of the sheet pile profiles. Chapter 4 presents the framework for assessing the measurement uncertainty of PECT and the propagation of this uncertainty in the assessment of the design value of the residual thickness. Chapter 5 outlines the conclusions of this investigation and suggestions for further steps towards the use of PECT for inspecting sheet pile walls.

## 2 Datasets of residual thickness

### 2.1 Introduction

The twelve sheet pile profiles used in this investigation were pulled out in 2023 from the Roggebot lock, that was located in the municipality of Dronten between the Drontermeer and de Vossemeer. The location of the sheet piles is shown in [Figure 2.1](#) and [Figure 2.2](#).



**Figure 2.1:** Location of the sheet pile profiles [retrieved from <https://www.destentor.nl/dronten/omleiding-bij-roggebotsluis-tussen-dronten-en-kampen-aangepast-om-sluipverkeer-tegen-te-gaan~a95ea508/>].



Figure 2.2: Sheet pile profiles used in this investigation.

The following datasets of measurements have been collected as part of this investigation:

- › Laser measurements in the laboratory setting, conducted by TNO.
- › PECT measurements in situ, conducted by SGS and RPS.
- › PECT measurements in the laboratory setting, conducted by SGS and RPS.
- › Ultrasound measurements in the laboratory setting, conducted by TNO.

## 2.2 Laser measurements

The measurement setup consists of two lasers and one wire transducer connected to a data acquisition system. The two lasers sensors are mounted on a frame, one below and one above the sheet pile, as shown in [Figure 2.3](#). In this way, the distance between the top and bottom of the section is measured in relation to the same reference point. The residual thickness is then obtained as the difference between the two measurements. At the same time, the distance between each measurement point and the beginning of the sheet pile profile is measured by the wire transducer.

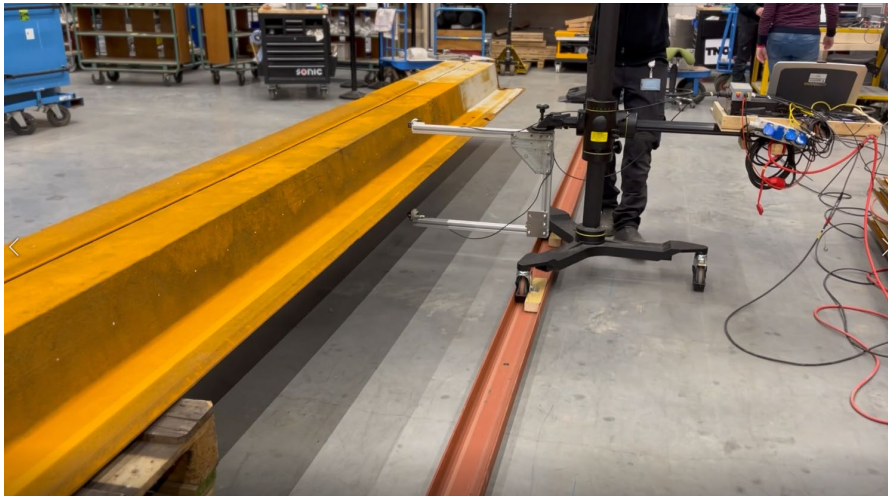


Figure 2.3: Set-up of the laser measurements.

The laser measurements were carried out in the longitudinal direction of the sheet piling along 5 measurement lines on each web and flange with spacing of 2 cm in the transverse direction, as shown in Figure 2.4. A measurement of the residual thickness was performed every millimetre.



Figure 2.4: Measurement lines (laser measurements).

Both the lasers and the wire transducer have been calibrated before performing the measurements. The calibration of the lasers has been performed by using the calibration blocks, while the distance measured by the wire transducer has been checked for given known distances.

## 2.3 PECT measurements

The PECT measurements were performed by the inspection companies SGS and RPS in-situ and later in the TNO laboratory. In the following, an overview of the measurements is given. More details about the measurement devices and the calibration can be found in the reports [2, 3].

## 2.3.1 In-situ measurements

The in-situ PECT measurements were performed in the middle of each flange and web, starting from a reference point 1 m above the waterline. This reference point has been marked on each element of the sheet pile profiles by a yellow circle, as shown in [Figure 2.5](#) around the mid-height of the light grey area of the sheet piles above the waterline. The sheet piles were not cleaned before performing the measurements.



**Figure 2.5:** Reference points [2].

The overview of the measurements is given in [Table 2.1](#), where the numbering of the flanges and webs is shown in [Figure 2.6](#).

**Table 2.1:** Overview of available in-situ PECT measurements (depth from the reference point – yellow circle in [Figure 2.5](#))

Sheet pile	Measured flanges/webs (SGS)	Measured flanges/webs (RPS)
I	1, 2, 5, 6 (up to a depth of 4 m)	1 (up to a depth of 3.75 m), 2 (up to a depth of 2.75 m), 3 (up to a depth of 3.0 m), 4 (up to a depth of 3.75 m), 5 (up to a depth of 2.75 m), 6 (up to a depth of 3.75 m)
II	1 (up to a depth of 4 m), 2 (up to a depth of 4 m), 5 (up to a depth of 2.75 m), 6 (up to a depth of 3.25 m)	1 (up to a depth of 3.75 m), 2 (up to a depth of 2.5 m), 3 (up to a depth of 3.75 m), 4 (up to a depth of 3.75 m), 5 (up to a depth of 2.25 m), 6 (up to a depth of 3.75 m)
III	1 (up to a depth of 3 m), 2 (up to a depth of 1.7 m), 5 (up to a depth of 3 m), 6 (up to a depth of 3 m)	1 (up to a depth of 3.75 m), 2 (up to a depth of 2.75 m), 3 (up to a depth of 3.25 m), 4 (up to a depth of 3.0 m), 5 (up to a depth of 2.5 m), 6 (up to a depth of 3.25 m)
IV	1 (up to a depth of 3 m), 2 (up to a depth of 2.25 m), 5 (up to a depth of 2.75 m), 6 (up to a depth of 2.75 m)	1 (up to a depth of 3.0 m), 2 (up to a depth of 3.0 m), 3 (up to a depth of 2.75 m), 4 (up to a depth of 2.25 m), 5 (up to a depth of 2.75 m), 6 (up to a depth of 2.5 m)
V	Not measured	1 (up to a depth of 2.75 m), 2 (up to a depth of 2.25 m), 3 (up to a depth of 2.25 m), 4 (up to a depth of 2.25 m), 5 (up to a depth of 2.25 m), 6 (up to a depth of 2.25 m)

Sheet pile	Measured flanges/webs (SGS)	Measured flanges/webs (RPS)
VI	Not measured	1 (up to a depth of 2.25 m), 2 (up to a depth of 2.25 m), 3 (up to a depth of 2.0 m), 4 (up to a depth of 1.75 m), 5 (up to a depth of 2.25 m), 6 (up to a depth of 2.0 m)

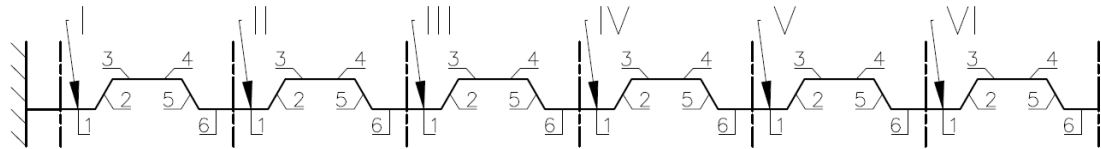


Figure 2.6: Numbering of the flanges and webs of the investigated sheet pile profiles.

### 2.3.2 Measurements in the laboratory

For the measurements in the laboratory, the two inspection companies selected a different grid of measurement points. RPS performed the measurements at the same locations as for the in-situ measurements. SGS performed one measurement every 10 cm above the waterline, one measurement every 2 cm for the first 90 cm below the waterline and one measurement every 10 cm for the remaining underwater part of the sheet piles. Measurements were not performed on the first profile of sheet pile I, because the first half of this element was damaged during the demolition of the lock. The overview of the measurements is given in Table 2.2.

Table 2.2: Overview of available PECT measurements performed in the laboratory (depth from the reference location – yellow circle in Figure 2.5)

Sheet pile	Measured flanges/webs (SGS)	Measured flanges/webs (RPS)
I	5, 6 (both up to a depth of 4 m)	4 (up to a depth of 3.75 m), 5 (up to a depth of 2.75 m), 6 (up to a depth of 3.75 m)
II	1, 2, 5, 6 (all up to a depth of 4 m)	1 (up to a depth of 3.75 m), 2 (up to a depth of 2.5 m), 3 (up to a depth of 3.75 m), 4 (up to a depth of 3.75 m), 5 (up to a depth of 2.25 m), 6 (up to a depth of 3.75 m)
III	1 (up to a depth of 4 m), 2 (up to a depth of 2.4 m), 5 (up to a depth of 4 m), 6 (up to a depth of 4 m)	1 (up to a depth of 3.75 m), 2 (up to a depth of 2.75 m), 3 (up to a depth of 3.25 m), 4 (up to a depth of 3.0 m), 5 (up to a depth of 2.5 m), 6 (up to a depth of 3.25 m)
IV	1, 2, 5, 6 (all up to a depth of 4 m)	1 (up to a depth of 3.0 m), 2 (up to a depth of 3.0 m), 3 (up to a depth of 2.75 m), 4 (up to a depth of 2.25 m), 5 (up to a depth of 2.75 m), 6 (up to a depth of 2.5 m)
V	Not measured	1 (up to a depth of 2.75 m), 2 (up to a depth of 2.25 m), 3 (up to a depth of 2.25 m), 4 (up to a depth of 2.25 m), 5 (up to a depth of 2.25 m), 6 (up to a depth of 2.25 m)
VI	Not measured	1 (up to a depth of 2.25 m), 2 (up to a depth of 2.25 m), 3 (up to a depth of 2.0 m), 4 (up to a depth of 1.75 m), 5 (up to a depth of 2.25 m), 6 (up to a depth of 2.0 m)

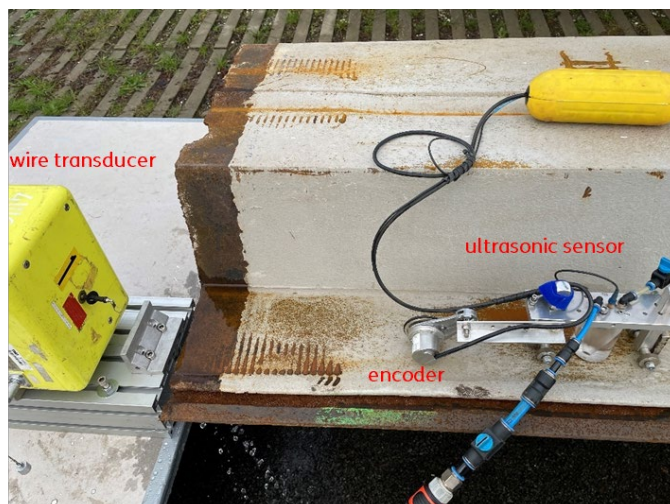
## 2.4 Ultrasonic measurements

Ultrasonic measurements were carried out by TNO in the laboratory only. These measurements have been performed approximately every millimetre in the middle of each flange and web (it corresponds to the measurement line in the middle shown in [Figure 2.7](#)).



**Figure 2.7:** Measurement lines (ultrasonic measurements).

The measurement device is shown in [Figure 2.8](#) and consists of three parts: the ultrasonic sensor, the encoder and a wire transducer. The ultrasonic sensor is an Olympus V312 with a focal distance of 25.4 mm and it is placed in a plexiglas cover into which water is injected. The ultrasonic sensor is mounted on a trolley with an encoder that triggers a measurement approximately every millimetre. The trolley is manually moved over the sheet piling. Upon triggering of the data acquisition system, an ultrasonic measurement is taken and the signal of the wire transducer is read to measure the absolute distance of the measurement point to the top of the sheet pile profile.



**Figure 2.8:** Measurement set-up (ultrasonic measurements).

The ultrasonic sensor has not been calibrated against reference calibration blocks, due to the unavailability of specimens of the steel with properties similar to those of the inspected sheet pile profiles. Therefore, the residual thickness has been estimated based on an assumed sound velocity of 5950 m/s in steel.

In order to assess the accuracy of the TNO ultrasonic measurements, these were compared with the measurements carried out by SGS to calibrate the PECT instrument and the laser measurements at the same location, 1 m above the waterline, where the sheet pile is not corroded. The measured values of the residual thickness are reported in [Table 2.3](#).

**Table 2.3:** Comparison between TNO and SGS ultrasonic measurements and laser measurements of sheet pile residual thickness

Sheet pile	Residual thickness						
	Laser [mm]	US (TNO) [mm]	US (SGS) [mm]	Sheet pile	Laser [mm]	US (TNO) [mm]	US (SGS) [mm]
I-4	11.1	10.9	10.4	IV-4	10.6	10.6	10.0
I-6	11.4	10.7	9.8	IV-5	9.4	9.5	10.9
II-1	10.6	11.0	10.7	IV-6	10.5	10.3	10.6
II-2	9.8	9.7	11.0	V-1	11.2	11.1	9.5
II-3	10.8	10.9	9.7	V-2	9.7	9.7	10.3
II-4	10.6	10.7	11.3	V-3	10.7	10.7	11.0
II-5	9.0	9.4	10.7	V-4	10.8	10.9	9.0
II-6	10.5	10.3	9.5	V-5	10.1	9.8	10.8
III-1	10.8	11.1	10.0	V-6	10.9	10.9	11.1
III-2	9.8	9.7	10.5	VI-1	10.7	10.5	9.8
III-3	11.3	10.9	9.3	VI-2	9.0	9.5	11.0
III-4	11.5	11.1	10.8	VI-3	10.3	10.2	10.6
III-6	10.5	10.8	11.0	VI-4	10.8	10.9	9.2
IV-1	10.4	11.1	9.8	VI-5	9.2	9.5	10.3
IV-2	10.1	9.9	10.9	VI-6	11.2	10.7	11.0

The difference between the ultrasonic measurement  $t_{US}$  and the laser measurement  $t_{laser}$  has been computed for each measurement point:

$$\Delta t = t_{US} - t_{laser} \tag{1}$$

Then the mean value  $\overline{\Delta t}$  and the sample standard deviation  $s_{\Delta t}$  of  $\Delta t$  have been determined based on the available 30 measurement points:

$$\overline{\Delta t} = \frac{1}{n} \sum_{i=1}^n \Delta t_i \tag{2}$$

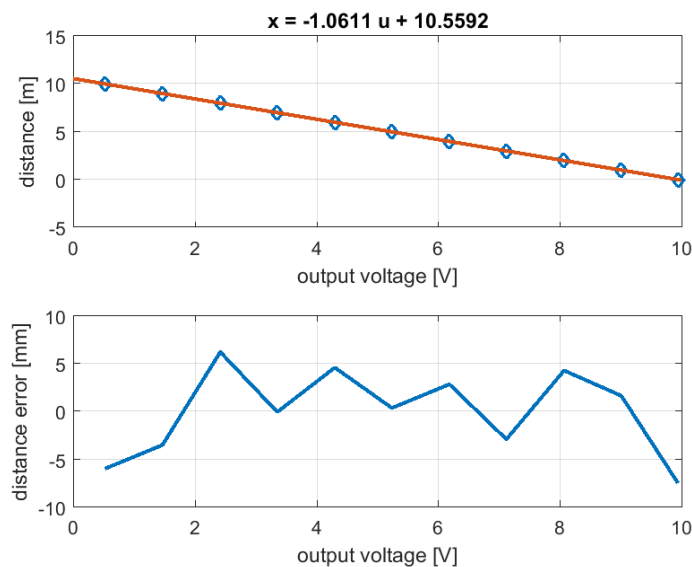
$$s_{\Delta t} = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (\Delta t_i - \overline{\Delta t})^2} \tag{3}$$

The values of  $\overline{\Delta t}$  and  $s_{\Delta t}$  for the TNO and SGS ultrasonic measurements are the following:

- › TNO:  $\overline{\Delta t} = 0.0 \text{ mm}$ ,  $s_{\Delta t} = 0.3 \text{ mm}$
- › SGS:  $\overline{\Delta t} = -0.1 \text{ mm}$ ,  $s_{\Delta t} = 0.4 \text{ mm}$

Based on these results, it can be concluded that, even though the ultrasonic device of TNO has not been calibrated, the ultrasonic measurements are in agreement with the laser measurement for the uncorroded part of the steel sheet pile walls. Furthermore, the TNO measurements are in agreement with the SGS measurements.

The wire transducer is calibrated prior to the measurements. The measured electrical voltage at the output of the wire transducer is converted into a distance measurement via a linear relationship, as shown in [Figure 2.9](#).



**Figure 2.9:** Calibration of wire transducer. Note the difference in scale of the top figure (m) and bottom figure (mm).

Due to non-linearities, there is an uncertainty in the measured distance in the longitudinal direction of  $\pm 5 \text{ mm}$ . The same uncertainty is estimated for the position in the transverse direction.

## 2.5 Preparation of the sheet pile profiles

Except for PECT, accurate laser and ultrasonic measurements require the steel surface of the sheet pile profile to be properly cleaned before performing the measurements. To this end, the sheet pile profiles have been cleaned three times, in the following order:

- › by the contractor, with high pressure water jetting, after pulling out the profiles
- › by TNO, with high pressure water jetting
- › by Straalbedrijf Schep by means of sandblasting.

The results of the three cleaning steps is shown in [Figure 2.10](#).



a) cleaning by the contractor with high pressure water jetting.



b) by TNO with high pressure water jetting.



c) by Straalbedrijf Schep by means of sandblasting.

**Figure 2.10:** Steel surface after cleaning of the sheet pile profiles.

# 3 Analysis of the corrosion patterns based on the laser measurements

## 3.1 Introduction

Before investigating the measurement uncertainty of PECT, a preliminary analysis of the corrosion patterns was carried out aiming to gain an insight into the corrosion zones in the direction of the depth of the sheet pile profiles. The laser measurements have been used for this purpose.

## 3.2 Corrosion zones

In order to determine the corrosion zones of the sheet pile structure, the average thickness loss is calculated for each flange and web at 10 cm intervals in the vertical direction as the difference between the initial thickness  $t_{initial}$  and the average residual thickness  $t_{residual,aver}$ :

$$\Delta t_{aver} = t_{initial} - t_{residual,aver} \quad (4)$$

In principle, measurements of the initial thickness along the sheet pile profiles should be used for this purpose. In absence of this information, the average residual thickness over the first meter of sheet pile from the top has been considered as the best guess of the initial thickness. The variation of the residual thickness along the first metre of the sheet pile profiles was estimated from the data to be less than 1% of the average thickness. As this value is very low, it can be concluded that the computed average thickness can be considered as a reliable indication of the initial thickness.

The location of the sheet pile profiles is shown in purple in the upper part of [Figure 3.1](#). The thickness loss as a function of the depth is also shown in the same figure.



The figure above shows that the thickness loss above the water line, which is approximately at NAP -0.2 m, is limited. The highest reductions of the thickness are observed in a part of the sheet pile with an extension of about 1 m in the vertical direction. This zone is followed by the remaining underwater zone characterized by a significantly lower thickness loss. On the right in the figure, it can also be observed that the thickness loss reduces systematically. This zone, marked in green, corresponds to the portion of the sheet piles embedded in the ground.

Since measurements were performed only above the ground level using PECT, three corrosion zones can be distinguished:

- › the zone above the water line, between NAP +1.6 m and NAP -0.2 m
- › the low water zone, between NAP -0.2 m and NAP -1.2 m
- › the underwater zone below NAP -1.2 m

# 4 Measurement uncertainty of PECT

## 4.1 Introduction

Measurements of physical properties of a structure, such as material properties and geometrical dimensions, are inevitably characterized by uncertainty, called measurement uncertainty. This chapter focusses on the measurement uncertainty of the PECT. The analysis is performed for both datasets of measurements obtained in-situ and in the laboratory. For this purpose, the concept of measurement uncertainty is explained first. Then, the measurement errors of PECT are evaluated and a simplified probabilistic model of the measurement uncertainty is presented.

## 4.2 Definition of measurement uncertainty

The result of a measurement is only an estimate of the value of the measurand, i.e. the quantity intended to be measured, and is complete only when accompanied by the statement of the uncertainty of that estimate. The uncertainty of a measurement reflects the lack of complete knowledge of the value of the measurand [3]. For this reason, a measurement result should be expressed as a single measured quantity value and a measurement uncertainty. In most applications, this is expressed as follows:

$$x = x_{meas} \pm U \quad (5)$$

where:

- $x$  is the measurand
- $x_{meas}$  is the measured quantity value, intended as the best estimate of the quantity attributable to the measurand  $x$
- $U$  is the measurement uncertainty

The parameter  $U$  can be the standard deviation (standard measurement uncertainty) or obtained by multiplying the combined standard uncertainty by a coverage factor  $k$  (expanded measurement uncertainty). The values of this factor is chosen on the basis of the sought confidence level. As an example, choosing  $k$  equal to 2 corresponds to a confidence level of 95%. In this case, the expression in Eq.(5) means that the probability that the interval  $[x_{meas} - U, x_{meas} + U]$  contains the unknown quantity intended to be measured is equal to 95%.

In this report, the measurement uncertainty is treated as a random variable and its probabilistic model (i.e. the distribution type, the mean value and standard deviation) is determined based on the analysis of the measurement errors, which are expressed as the difference between the measurement value and the reference value of the measurand. In this investigation, the residual thickness of sheet pile profiles is the measurand of interest.

## 4.3 Assessment of the measurement uncertainty of PECT

In the following, the laser measurements are considered as the reference values of the residual thickness. Therefore, the measurement errors of PECT are defined as the difference between the PECT value and the laser value of the residual thickness at the same measurement point:

$$\text{measurement error} = t_{PECT} - t_{laser} \tag{6}$$

In the following, the measurement errors are evaluated separately for the measurements performed in-situ and in the laboratory.

### 4.3.1 Measurement errors in-situ

The PECT measurements are compared with the laser ones in the figures below. Since the comparison between the companies is not of interest for this study, they are referred to as “inspection company A” and “inspection company B” in the following. The PECT value of the residual thickness at a given measurement point is the average residual thickness over the footprint area, which includes the probe area and the lift-off of the probe from the steel surface [2, 3]. Therefore, the average residual thickness based on the laser measurements given on the horizontal axis is computed on the same footprint area.

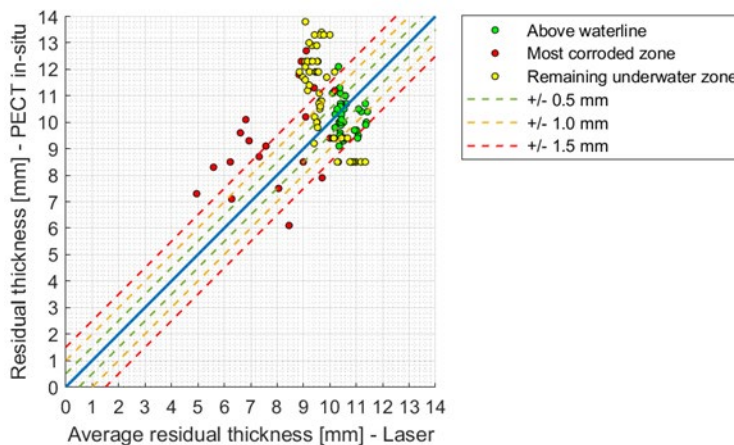


Figure 4.1: Measurement errors – flanges (inspection company A).

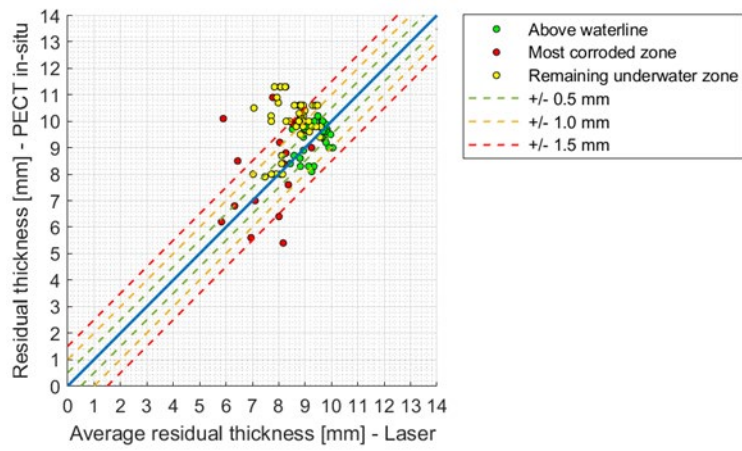


Figure 4.2: Measurement errors – webs (inspection company A).

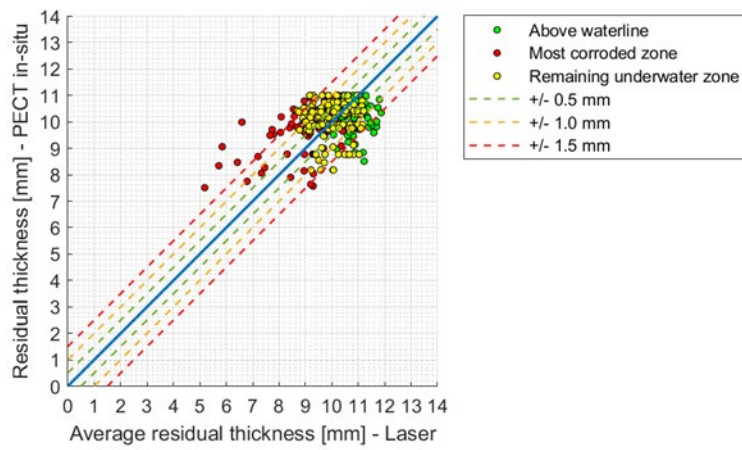


Figure 4.3: Measurement errors – flanges (inspection company B).

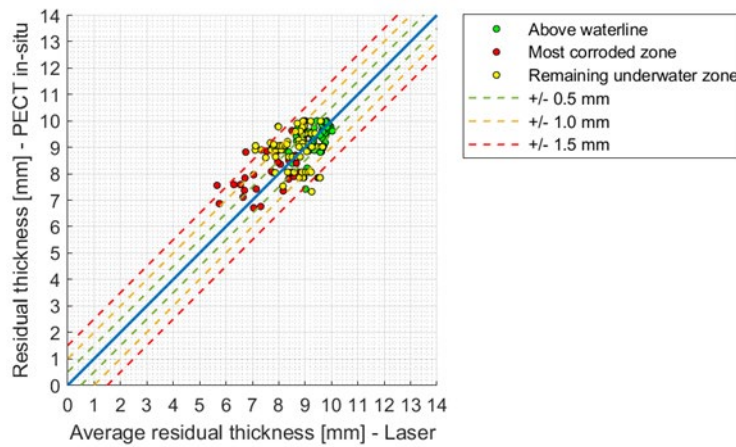


Figure 4.4: Measurement errors – webs (inspection company B).

It can be observed in Figure 4.1 and Figure 4.2 that, for some measurement points in the remaining under water zone, PECT overestimates the true residual thickness of the profiles. As discussed in [2], these deviations arise from the drifting of the measurement set-up used in situ.

Further elaboration of the data presented in the plots shows that:

- › 35% of the PECT measurements are within  $\pm 0.5$  mm of the laser measurement
- › 65% of the PECT measurements are within  $\pm 1.0$  mm of the laser measurement
- › 81% of the PECT measurements are within  $\pm 1.5$  mm of the laser measurement
- › 19% of the PECT measurements are outside  $\pm 1.5$  mm of the laser measurement

### 4.3.2 Measurement errors in the laboratory

The PECT measurements performed by SGS and RPS are compared with the laser ones in the figures below.

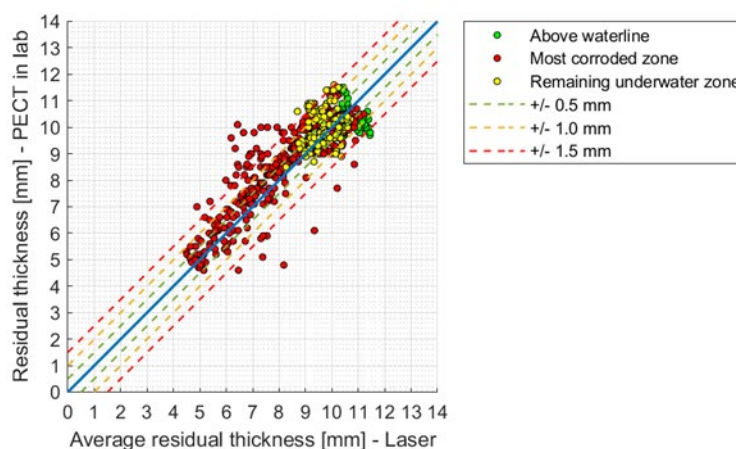


Figure 4.5: Measurement errors – flanges (inspection company A).

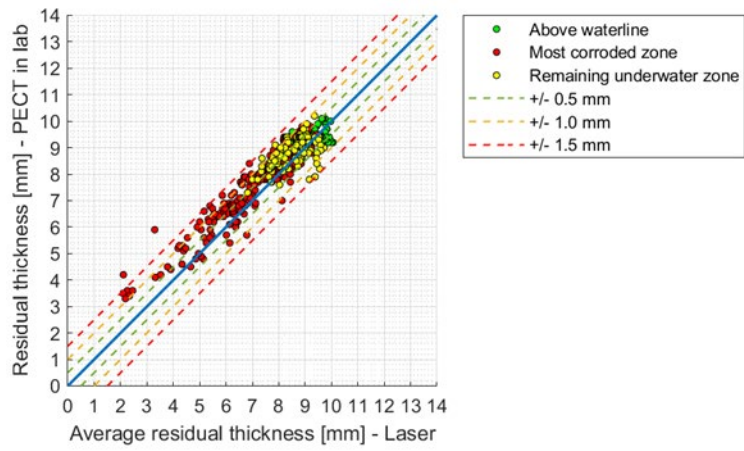


Figure 4.6: Measurement errors – webs (inspection company A).

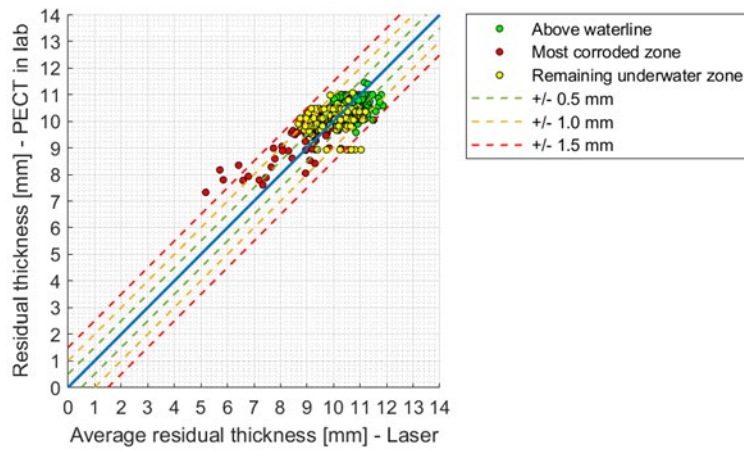


Figure 4.7: Measurement errors – flanges (inspection company B).

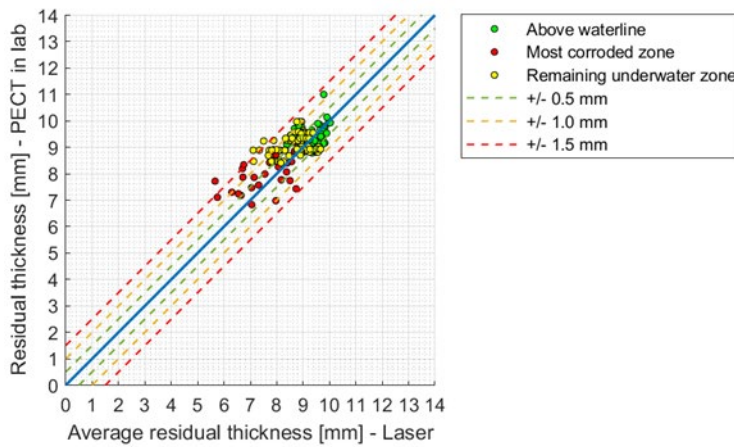


Figure 4.8: Measurement errors – webs (inspection company B).

The following statistics have been estimated for the measurements in the laboratory:

- › 50% of the PECT measurements are within  $\pm 0.5$  mm of the laser measurement
- › 85% of the PECT measurements are within  $\pm 1.0$  mm of the laser measurement
- › 95% of the PECT measurements are within  $\pm 1.5$  mm of the laser measurement
- › 5% of the PECT measurements are outside  $\pm 1.5$  mm of the laser measurement

As expected, the errors of the measurements performed in the laboratory are significantly lower than the errors of the in-situ measurements.

## 4.4 Comparison between PECT and ultrasonic measurements

A further comparison is performed between the PECT measurements and the ultrasonic measurements, both performed in the laboratory. For each measurement point used by SGS in the laboratory, the average residual thickness has been determined based on the laser and ultrasonic measurements on the footprint of the PECT probe. The deviation of the ultrasonic measurements is remarkable and occurs in most of the corroded zone of the sheet pile sections.

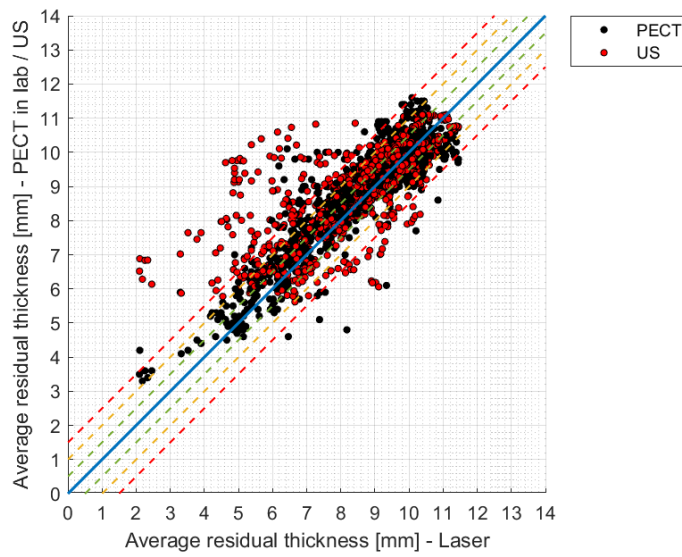


Figure 4.9: Comparison between PECT and ultrasonic measurements.

## 4.5 Measurement uncertainty

The observations of the measurement uncertainty as a function of the laser value of the residual thickness are shown in the figures below for the measurements in the laboratory and in situ.

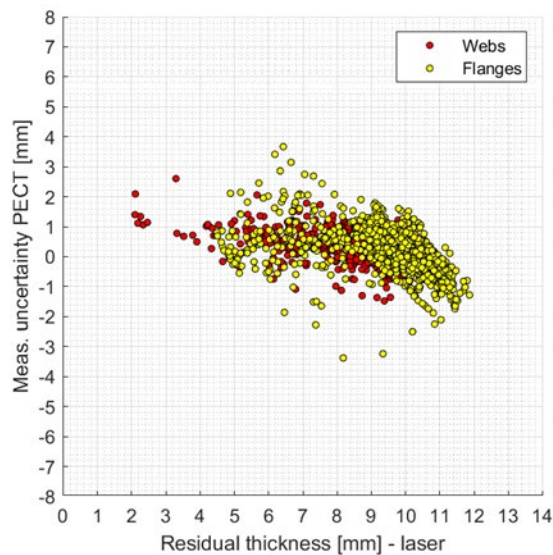


Figure 4.10: Measurement uncertainty based on measurements performed in the laboratory.

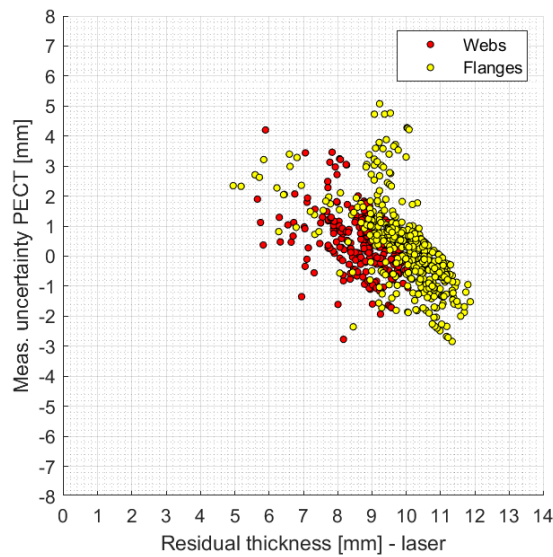


Figure 4.11: Measurement uncertainty based on in-situ measurements.

A Normal distribution has been fitted to the two datasets separately. The mean value and standard deviation are listed in Table 4.1.

Table 4.1: Parameters of the normal distribution of the measurement uncertainty.

Measurement	Mean value [mm]	Standard deviation [mm]
In the laboratory	0.23	0.70
In-situ	0.35	1.25

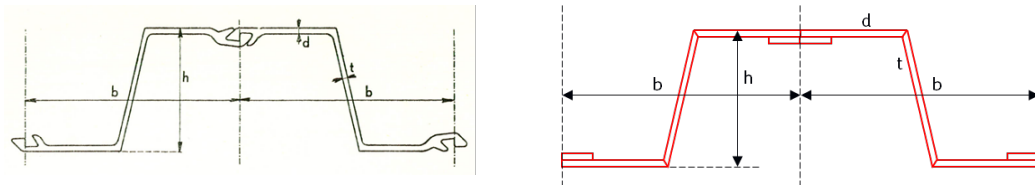
The positive mean value means that, on average, PECT overestimates the true thickness of the sheet pile profiles. This suggests that the calibration of this measurement technique should be performed to obtain unbiased estimates of the residual thickness. As expected, the standard deviation of the measurement uncertainty is higher in-situ than in laboratory conditions. Therefore, the lessons learned in this measurement campaign should be used to improve the measurement set-up used in the field [2, 3].

## 4.6 Effect of the measurement errors on the resistance of the sheet pile wall

When assessing the safety of sheet pile structures, the stress in the steel wall is computed by using the elastic section modulus  $W_{el}$  based on the axial force and bending moment estimated, usually estimated using 2D plane-strain models of the structure. In this calculation, the elastic section modulus is computed per meter of length of the structure in the longitudinal direction. When accounting for the effects of corrosion on the safety the sheet pile structure, the calculation of the elastic section modulus should be performed in horizontal planes at various depths considering the sheet pile profiles within the length of the governing failure mechanism in the longitudinal direction of the sheet pile structure. In case of anchored sheet piling, the mechanism length is assumed equal to the distance between two consecutive anchors.

To assess the effect of the measurement errors of PECT at the structural level, the elastic section modulus  $W_{el}$  is computed here at various depths for the whole set of sheet pile profiles

made available from the Roggebot lock. This calculation is performed at all depths at which PECT and laser measurements of the residual thickness are considered (see section 3). The elastic section modulus of sets of consecutive corroded sheet pile profiles is based on a simplified geometrical model of the cross-section, as shown in [Figure 4.12](#) for two profiles. The dimensions of the cross-section of the Belval B.Z. IIR profile are listed in [Table 4.2](#).



**Figure 4.12:** Simplified geometrical model of the cross-section. Left: actual geometry, right: simplified geometry.

**Table 4.2:** Nominal dimensions of the profile Belval B.Z. IIR

Property	Symbol	Value [mm]
Width	b	450
Height	h	222
Thickness of the flanges	d	11
Thickness of the web	t	10

The simplified geometrical model is based on the following assumptions:

- ) the webs and flanges are modelled by parallelograms
- ) interlocks are modelled by rectangular shapes, with height equal to the thickness of the flanges, while the base is calibrated to match the elastic section modulus  $W_{el}$  of the uncorroded Belval II R profile
- ) corrosion is considered only on the water side.

The values of the elastic section modulus obtained based on the laser and the PECT technique are compared in [Figure 4.13](#). It can be observed that, despite some considerable measurement errors, the impact of these errors on the elastic section modulus is quite limited and it amounts to 10%.

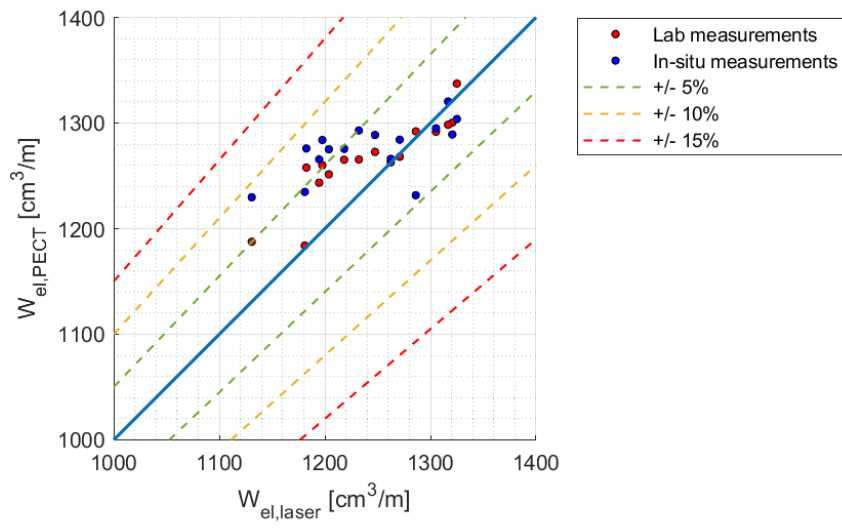


Figure 4.13: Comparison of elastic section modulus based on laser and PECT measurements.

## 5 Conclusions and recommendations

The advantage of Pulsed Eddy Current Testing (PECT) for the inspection of existing sheet piling is that the probe does not need to be applied to a clean surface. Therefore, PECT is potentially suitable for assessing the residual thickness in an efficient (no cleaning is needed) and in a safe way (divers are not required for underwater inspections). It should be however taken into account that the PECT measurements are not pointwise measurements, but an average value taking into account the contact area of the probe and the lift-off from the steel surface. Therefore, these measurements can support the safety assessment in case that the structure is not prone to corrosion-induced holes, as in the case of microbially induced corrosion (MIC).

Since PECT is not a state-of-the-art inspection technique for the inspection of sheet piles, Rijkswaterstaat has asked TNO to perform an investigation on the measurement uncertainty of the PECT technique. To this end, measurements of the residual thickness have been performed on 12 sheet pile profiles, that were pulled out from the Roggebot lock in 2023. Three types of measurements have been performed:

- ) PECT measurements in the field (before the demolition of the lock)
- ) PECT measurements in the laboratory
- ) laser measurements in the laboratory.

In addition, ultrasonic measurements were performed in the laboratory to benchmark PECT with the state-of-the-art inspection technique for sheet pile walls. A quantitative analysis of the differences between the PECT measurements and the laser measurements has been performed, resulting in the assessment of the measurement uncertainty of PECT.

From this study, the following conclusions can be drawn:

- ) the external conditions during the measurements (in-situ vs. laboratory conditions) can significantly affect the accuracy of PECT measurements
- ) the vast majority of the PECT measurement errors do not exceed  $\pm 1.5$  mm, but some errors can be significant and on the unsafe side (overestimation of the residual thickness)
- ) the PECT measurements are no less reliable than the ultrasonic ones
- ) the effect of measurement errors on the section modulus of the sheet pile structure was found to be limited for the considered sheet pile profiles.

Before PECT is used systematically for the inspection of existing sheet pile structures, it is recommended to:

- ) perform a second measurement campaign, focussing on improving the measurement set-up used in the field
- ) develop a measurement protocol for PECT with requirements and recommendations aiming to limit the effect of the in-situ conditions on the accuracy of the measurements

## 6 References

[1] CROW (2021). Protocol gemiddelde staaldiktebepaling van 6 aangrenzende stalen damwandplanken met ultrasone metingen. Kennisplatform CROW.

[2] Meijninger, R. & Crouzen, P. (2023). Pulsed Eddy Current Testing (PECT). Proeven Roggebotsluis 6 april 2023.

[3] de Rijke, B. (2023). Inspectierapportage PECT-staaldiktemetingen Damwandconstructie Roggebotsluis & Damwand TNO Delft

[4] Joint Committee for Guides in Metrology (2012). JCGM 200:2012. International vocabulary of metrology - Basic and general concepts and associated terms (VIM).

[5] Joint Committee for Guides in Metrology (2008). JCGM 100:2008. Evaluation of measurement data - Guide to the expression of uncertainty in measurement.

# 7 Signature

TNO › Mobility & Built Environment › Delft, 30 July 2025

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