Parallelsessie KPNK symposium:

Nieuwe Inspectietechieken & damwanden

Evaluating measurement uncertainty of PECT and PAUT techniques based on measurements of residual thickness of sheet piles

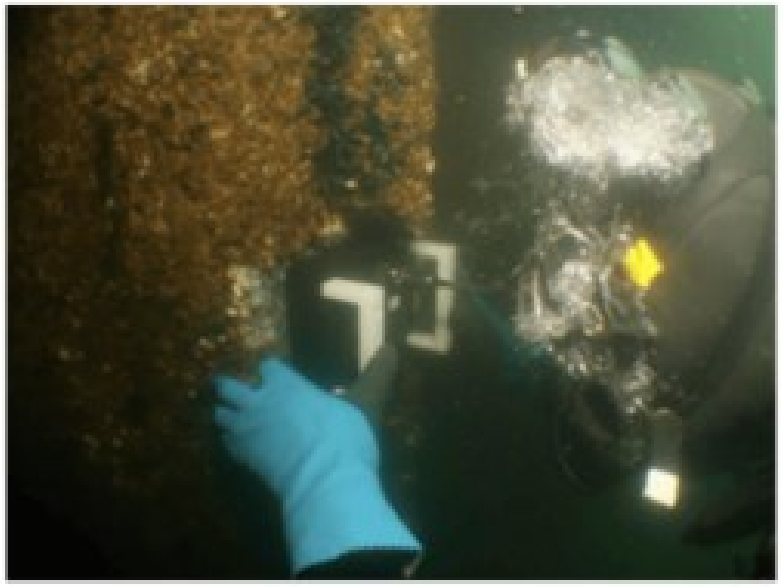
Ece Ozer (TNO)

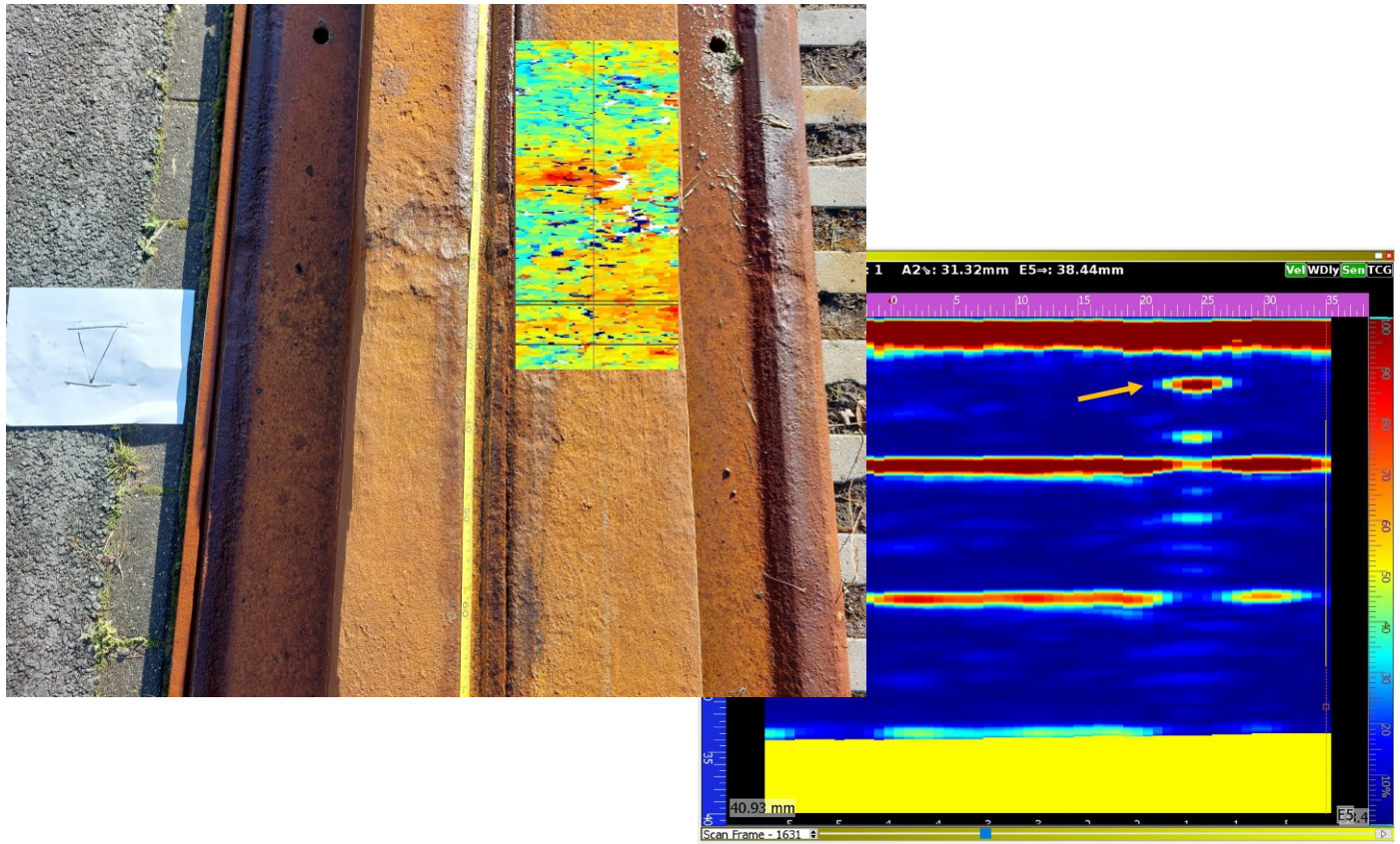
Diego Allaix (TNO)

3 februari 2025

Non-traditional measurement techniques for sheet pile inspection

- Pulsed Eddy Current Testing (PECT) → no divers needed.
- Phased Array Ultrasonic Testing (PAUT) → full scan, instead of point-wise measurements

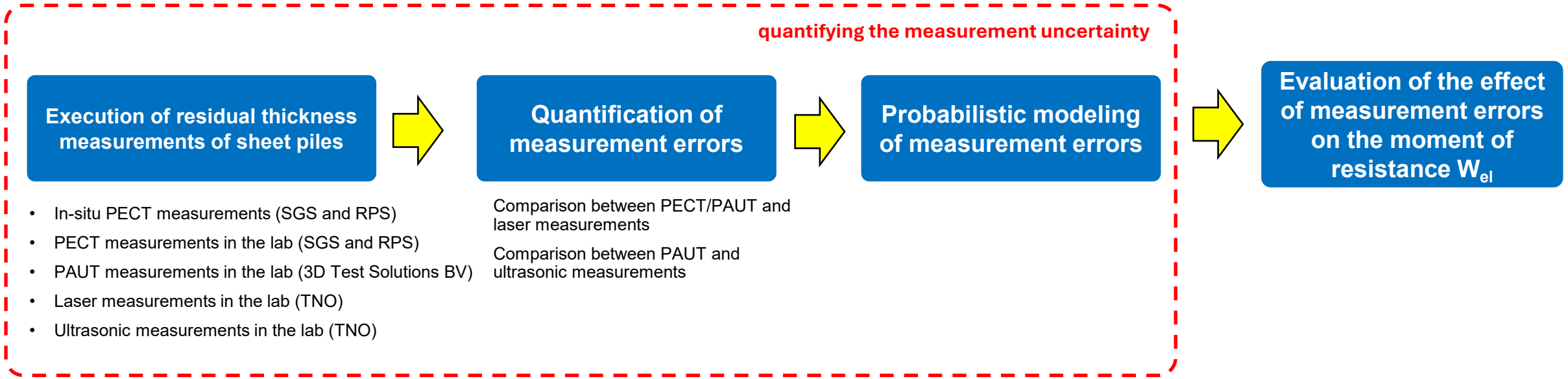




Non-traditional measurement techniques for sheet pile inspection

Objective: To quantify the measurement uncertainty of Pulsed Eddy Current Testing (PECT) and Phased Array Ultrasonic Testing (PAUT) techniques

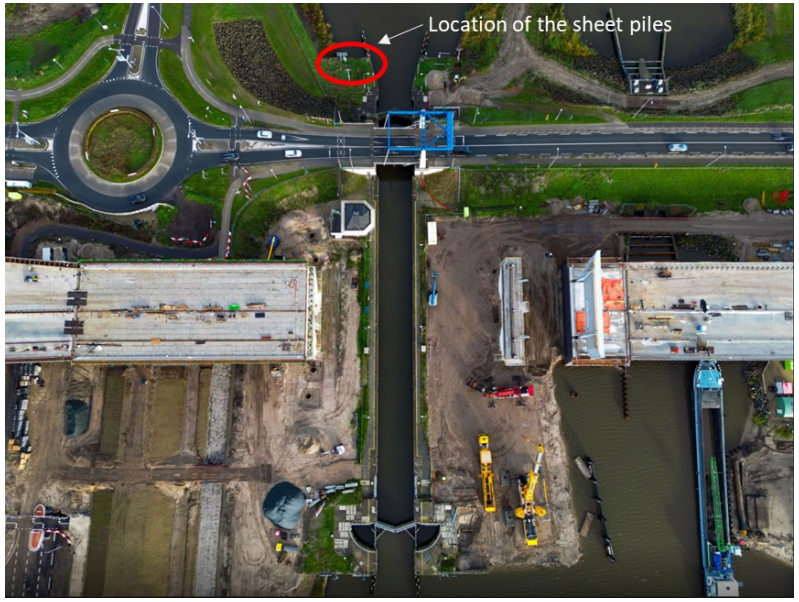
Approach:

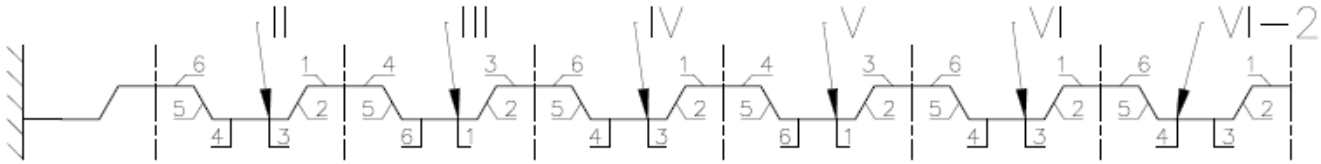


KENNISPROGRAMMA
NATTE KUNSTWERKEN

Measurements of the residual thickness of sheet pile walls

- The Roggebot sluice
- 12 Belval IIR sheet pile profiles (1956: year of installation)

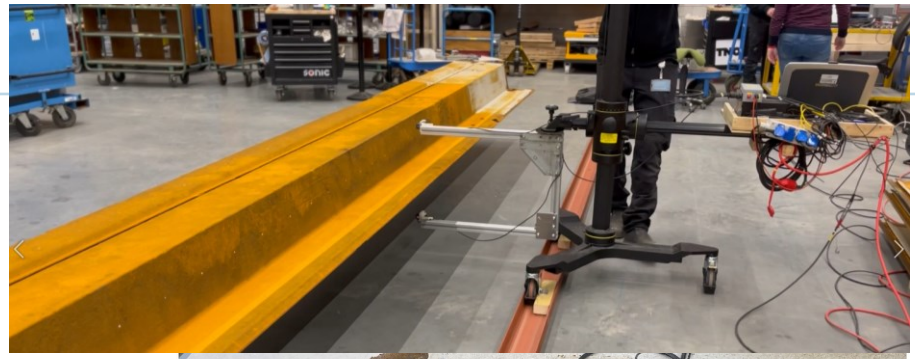


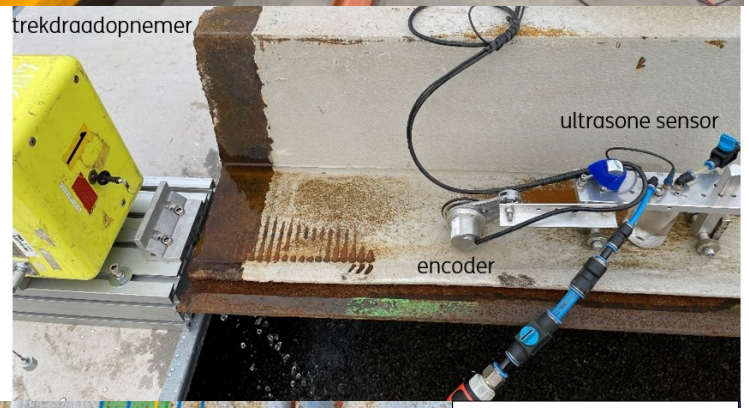


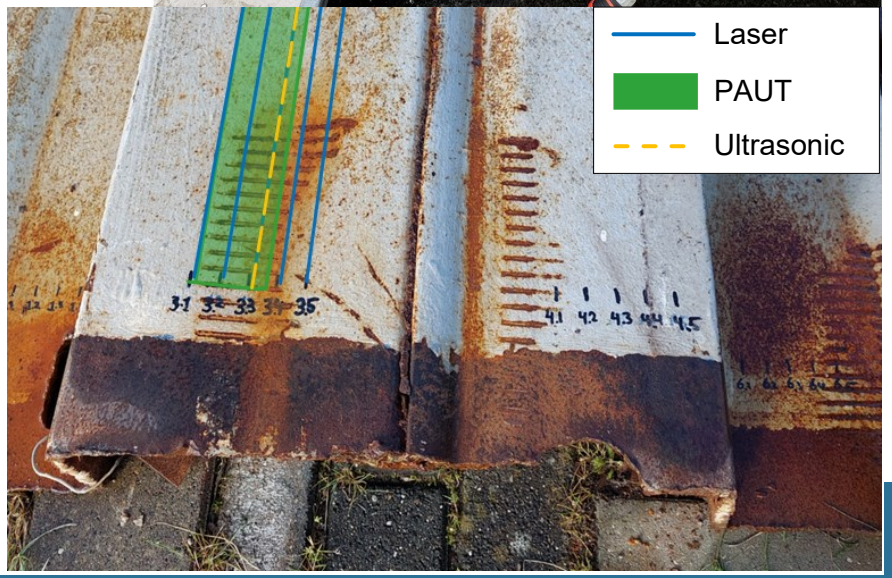
KENNISPROGRAMMA
NATTE KUNSTWERKEN

The Datasets

- **Laser measurements** (TNO):
  - 5 measurement lines per web/flange with spacing of 2 cm in the transverse direction
  - 1 measurement every ~ 1 mm gap in the longitudinal direction
- **Ultrasonic measurements** (TNO):
  - 1 measurement line in the middle of each web/flange
  - 1 measurement every ~ 1 mm gap in the longitudinal direction
- **PAUT measurements** (3-DTS):
  - 57 measurement lines per web/flange with a spacing of 1 mm in the transverse direction
  - 1 measurement every 1 mm gap in the longitudinal direction



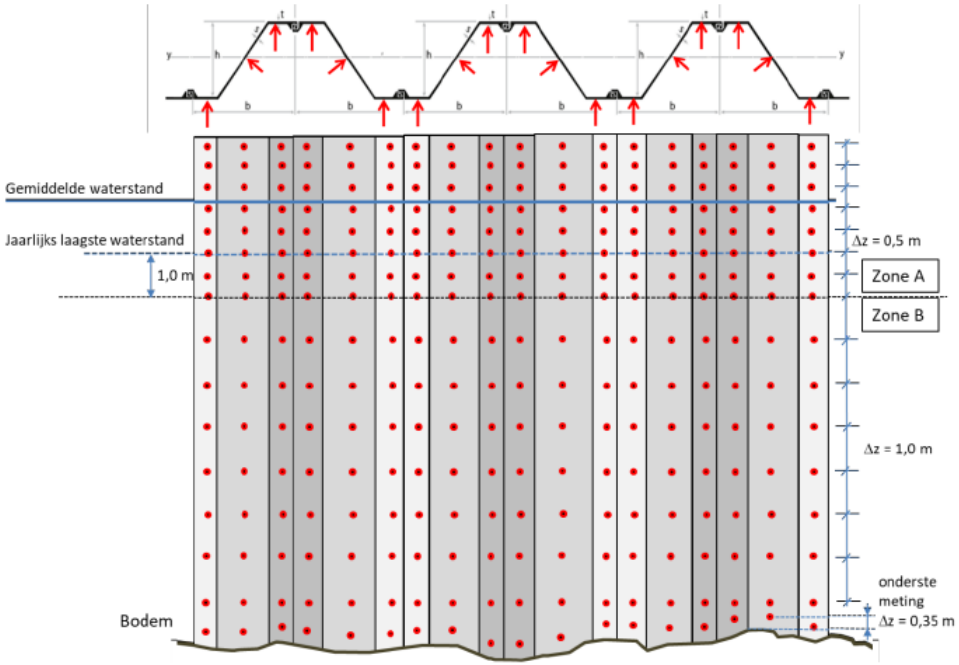




The Datasets

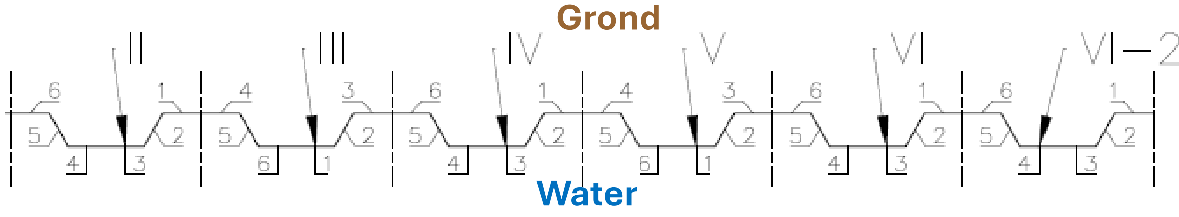
- **In-situ PECT measurements (SGS and RPS):** 1 measurement every 25 cm, starting 1 m above the waterline, for a total length of 4 m

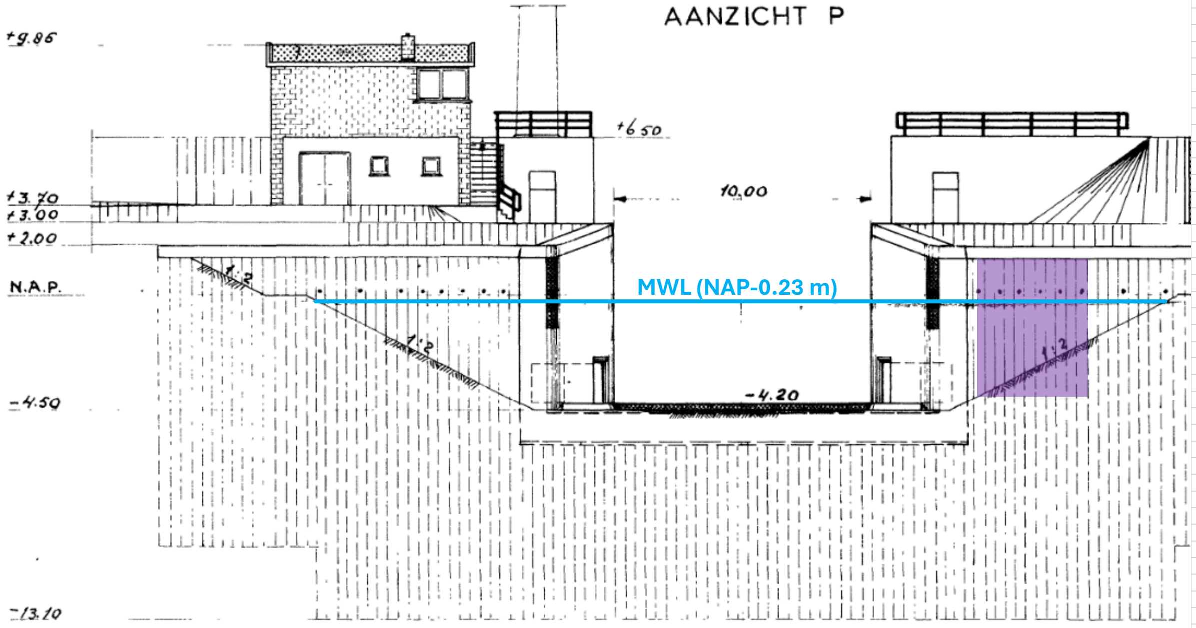
- **PECT measurements in the lab (SGS and RPS)**
  - **SGS**
    - 1 measurement every 10 cm above the waterline
    - 1 measurement every 1-2 cm in the first 90 cm below the waterline
    - 1 measurement every 10 cm for the next 2.1 m below the waterline
  - **RPS:** 1 measurement every 25 cm, starting 1 m above the waterline, for a total length of 4 m



Laser measurements of the residual thickness of sheet piles

Overview of the corrosion patterns





z [m t.o.v. NAP]	Thickness loss [mm]																																			
	2-6	2-5	2-4	2-3	2-2	2-1	3-6	3-5	3-4	3-3	3-2	3-1	4-6	4-5	4-4	4-3	4-2	4-1	5-6	5-5	5-4	5-3	5-2	5-1	6-6	6-5	6-4	6-3	6-2	6-1	7-6	7-5	7-4	7-3	7-2	7-1
1.6	0.1		0.0	0.1	0.1	0.0	0.0	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.1	0.2	0.0	0.1	0.1	0.1
1.5	0.0		0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.1	0.1	0.0	0.1
1.4	0.1		0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.3	0.1		0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.2	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
1.1	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.0	0.0		0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.9	0.0		0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.8	0.0		0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.7	0.0		0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.6	0.0		0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.5	0.0		0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
0.4	0.0		0.1	0.1	0.0	0.3	0.1	0.0	0.0	0.1	0.1	0.2	0.2	0.1	0.0	0.0	0.1	0.2	0.0	0.0	0.1	0.0	0.1	0.1	0.0	0.1	0.0	0.0	0.2	0.0	0.0	0.1	0.0	0.0	0.0	0.0
0.3	0.0		0.1	0.2	0.1	0.3	0.1	0.1	0.0	0.1	0.1	0.2	0.3	0.2	0.0	0.0	0.2	0.1	0.0	0.1	0.0	0.0	0.1	0.1	0.1	0.2	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	0.0	0.0
0.2	0.0		0.1	0.2	0.1	0.4	0.2	0.2	0.0	0.1	0.1	0.3	0.4	0.3	0.1	0.0	0.2	0.1	0.1	0.2	0.0	0.0	0.1	0.1	0.1	0.2	0.0	0.0	0.3	0.2	0.1	0.1	0.1	0.0	0.1	0.0
0.1	0.0		0.1	0.2	0.2	0.5	0.2	0.3	0.1	0.0	0.2	0.5	0.6	0.4	0.2	0.0	0.2	0.2	0.3	0.5	0.0	0.1	0.2	0.2	0.4	0.3	0.0	0.0	0.2	0.2	0.3	0.2	0.1	0.0	0.1	0.0
0.0	0.1		0.1	0.1	0.4	0.4	0.3	0.4	0.3	0.0	0.5	0.4	0.7	0.4	0.2	0.0	0.3	0.1	0.2	0.2	0.1	0.1	0.2	0.2	0.2	0.3	0.0	0.0	0.3	0.2	0.3	0.2	0.2	0.0	0.1	0.0
-0.1	0.0		0.3	0.2	0.6	0.4	0.4	0.6	0.2	0.2	0.6	0.5	0.9	0.6	0.5	0.2	0.5	0.4	0.6	0.4	0.3	0.1	0.3	0.2	0.6	0.3	0.2	0.3	0.5	0.3	0.4	0.3	0.4	0.2	0.1	0.2
[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
-0.3	1.1		1.5	1.2	1.5	2.0	1.6	1.2	1.8	2.6	1.4	1.9	1.2	1.9	2.7	2.5	1.0	0.9	0.7	1.8	1.6	0.8	1.7	0.4	1.1	1.0	1.1	1.1	1.4	1.6	1.1	1.0	1.4	1.1	1.0	1.1
-0.4	2.1		6.1	5.3	3.7	2.8	2.9	3.6	3.3	4.8	2.7	2.2	2.2	6.2	5.7	4.9	4.5	1.1	1.7	4.4	5.1	2.3	4.3	0.8	3.0	2.6	5.3	4.9	3.7	3.3	2.4	3.0	5.6	1.4	3.1	1.4
-0.5	1.3		5.1	3.3	2.8	1.9	1.5	2.8	3.8	4.9	4.1	1.6	1.8	4.7	5.0	5.1	2.7	1.6	2.6	3.1	5.0	5.5	3.2	1.9	1.1	2.9	4.3	3.6	2.9	2.0	2.3	3.5	4.1	1.6	2.3	1.6
-0.6	1.2		4.4	4.0	1.3	1.5	1.2	3.3	3.5	4.3	2.0	1.1	1.2	2.4	2.7	4.4	1.5	1.5	1.3	2.1	4.9	5.5	2.1	1.4	1.1	2.5	2.1	3.7	2.3	1.5	1.8	2.8	2.9	2.6	1.4	2.6
-0.7	1.0		2.6	3.4	1.3	1.3	1.5	2.8	2.9	2.7	1.1	1.3	1.5	1.7	1.7	2.2	1.1	1.2	1.8	1.6	3.1	3.4	1.9	1.2	1.0	1.8	1.5	2.8	1.9	1.4	1.7	2.2	1.7	1.2	1.2	1.2
-0.8	0.7		1.5	2.5	1.1	1.2	1.0	2.3	1.4	2.0	0.9	1.1	1.4	1.3	1.3	1.2	1.0	1.0	1.6	1.3	1.6	2.2	1.2	1.2	1.2	1.2	0.9	1.9	1.3	1.8	1.7	1.7	1.6	1.3	0.8	1.3
-0.9	0.8		1.1	2.0	0.9	1.3	0.8	1.2	1.0	1.0	0.8	1.1	1.3	1.6	0.9	0.9	1.0	1.0	1.1	1.8	1.2	2.3	1.4	1.2	1.1	1.2	1.0	1.4	1.2	1.6	1.5	1.3	0.8	1.0	1.1	1.0
-1.0	0.9		0.9	1.3	0.9	1.2	1.1	1.2	1.1	0.9	0.8	1.0	1.2	1.1	1.0	1.2	0.9	1.2	1.4	1.3	1.2	2.0	1.3	1.3	1.7	1.1	1.0	1.4	1.8	1.6	1.3	1.3	0.9	0.8	1.1	0.8
-1.1	0.8		0.8	1.0	0.9	1.3	1.1	0.9	1.0	1.0	0.7	1.0	1.1	1.1	1.4	1.5	1.2	1.4	1.0	1.2	1.5	1.6	1.3	1.3	1.9	0.8	0.8	1.4	1.2	1.2	1.8	1.2	0.9	0.9	0.7	0.9
-1.2	0.8		1.0	1.4	1.0	1.2	1.5	0.7	1.0	1.0	0.8	0.9	1.2	1.4	1.4	1.0	1.2	1.2	1.6	1.4	1.1	1.5	0.8	1.6	1.5	0.8	1.0	0.7	0.8	1.0	1.5	1.1	0.7	0.6	0.6	0.6
-1.3	1.4		1.3	1.2	0.8	1.6	1.4	0.7	0.6	0.8	0.9	1.1	1.6	1.3	1.3	0.9	1.1	1.1	1.2	1.2	1.3	1.2	0.8	1.6	1.3	1.0	0.7	0.8	1.3	1.7	1.3	0.9	0.7	0.5	0.6	0.5
-1.4	1.3		1.2	1.3	1.0	1.8	1.4	1.0	0.7	0.9	0.8	1.1	1.7	1.3	1.3	1.0	1.0	1.2	1.5	1.0	1.3	0.8	1.0	2.0	0.8	0.8	0.4	1.0	0.9	1.4	0.7	0.8	0.8	0.4	0.4	0.4
-1.5	1.0		1.2	1.3	1.1	1.9	1.6	1.1	1.1	0.9	1.1	1.3	1.7	1.7	1.2	1.1	1.0	1.5	2.1	1.1	1.3	0.8	1.0	1.8	0.5	1.0	1.3	0.6	0.7	1.0	0.3	0.5	0.3	0.5	0.3	0.5
-1.6	1.2		1.2	1.3	0.8	1.4	2.0	2.0	1.1	0.9	0.9	1.3	1.9	1.8	1.4	1.4	1.0	1.5	1.4	0.9	1.3	1.2	0.6	1.3	1.1	1.2	0.8	0.9	0.7	1.0	0.5	0.4	0.4	0.3	0.2	0.3
-1.7	1.2		1.0	1.2	0.8	1.4	1.4	1.8	1.0	0.8	0.7	1.0	1.4	1.3	2.2	1.2	1.5	1.4	1.2	1.2	1.5	1.0	1.3	0.6	0.7	0.7	1.0	0.7	0.5	0.5	0.2	0.3	0.3	0.2	0.2	0.2
-1.8	0.8		1.3	1.1	1.0	1.4	1.1	1.1	1.1	0.9	0.8	1.1	1.1	1.1	1.3	1.1	1.3	1.4	1.2	1.1	1.1	0.8	0.9	1.1	0.5	0.6	0.7	0.5	0.7	0.8	0.2	0.3	0.2	0.0	0.3	0.0
-1.9	0.9		1.1	1.1	1.0	1.3	1.1	1.0	0.7	1.0	0.8	1.2	1.3	0.9	1.1	1.1	1.2	1.6	1.1	0.9	0.8	1.1	0.5	1.1	0.4	0.6	0.3	0.3	0.8	0.7	0.2	0.8	0.4	0.0	0.1	0.0
-2.0	0.7		0.9	1.1	0.9	1.1	1.2	0.9	0.7	0.9	0.8	0.9	1.1	0.8	1.2	1.2	0.9	1.1	0.8	1.6	0.8	0.5	0.3	0.5	0.2	0.4	0.2	0.3	0.8	0.7	0.5	1.0	0.6	0.0	0.0	0.0
-2.1	0.8		0.8	1.1	0.8	1.2	1.4	0.8	0.7	1.2	0.9	0.9	1.1	1.0	1.3	1.4	1.5	1.9	1.1	1.1	1.0	0.2	0.3	0.6	0.1	0.4	0.3	0.3	0.6	0.6	0.6	1.0	0.3	0.0	0.1	0.0
-2.2	0.5		0.9	1.1	0.9	1.2	0.9	0.9	0.8	0.9	0.7	1.0	1.1	1.3	1.5	1.3	1.1	1.0	0.6	0.5	0.6	0.5	0.4	0.8	0.2	0.3	0.2	0.3	0.6	0.7	0.8	0.9	0.3	0.0	0.1	0.0
-2.3	0.5		0.9	1.0	0.9	1.0	0.7	1.0	0.8	0.8	0.9	0.9	1.4	1.1	1.2	0.9	0.7	0.8	0.6	0.4	1.0	0.4	0.3	0.4	0.7	0.3	0.5	0.2	0.6	0.6	0.7	0.8	0.2	0.1	0.1	0.1
-2.4	0.4		1.1	1.0	0.9	0.9	0.6	0.8	0.6	0.8	0.9	1.2	1.0	1.2	1.2	0.6	0.6	0.5	0.4	0.2	0.5	0.3	0.3	0.2	0.1	0.2	0.4	0.3	0.6	0.3	0.6	0.4	0.0	0.4	0.2	0.4
-2.5	0.4		1.1	0.9	0.9	0.9	0.7	0.8	0.4	0.9	0.7	0.8	0.8	1.1	0.8	0.4	0.3	0.5	0.6	0.2	0.2	0.2	0.3	0.1	0.1	0.2	0.0	0.3	0.5	0.2	0.2	0.2	0.1	0.1	0.4	0.1
-2.6	0.3		0.8	0.9	0.9	0.9	0.8	0.7	0.5	1.0	0.6	1.9	0.5	0.7	1.0	0.3	0.4	0.4	0.4	0.1	0.3	0.2	0.2	0.1	0.0	0.2	0.3	0.3	0.4	0.3	0.4	0.3	0.4	0.0	0.2	0.0
-2.7	0.5		0.9	0.9	0.9	1.1	1.1	1.0	0.8	0.6	0.8	1.0	0.9	0.6	0.7	0.3	0.4	0.5	0.5	0.4	0.5	0.1	0.2	0.0	0.0	0.5	0.3	0.0	0.4	0.4	0.2	0.2	0.1	0.0	0.1	0.0
-2.8	0.5		0.7	1.0	1.0	1.2	0.9	1.9	1.1	1.0	0.4	0.7	1.0	0.7	0.8	0.4	0.4	0.5	1.0	0.5	0.9	0.0	0.2	0.0	0.0	0.6	0.4	0.0	0.3	0.1	0.0	0.2	0.0	0.1	0.1	0.1
-2.9	0.7		1.0	1.0	0.7	1.2	1.1	1.4	1.3	0.6	0.3	0.8	0.6	0.9	1.2	0.4	0.5	0.6	1.1	0.6	0.7	0.0	0.2	0.1	0.0	0.7	0.3	0.0	0.3	0.2	0.0	0.2	0.0	0.1	0.0	0.1
-3.0	0.7		1.2	1.1	1.2	0.8	1.7	1.4	0.8	0.5	0.3	1.2	0.7	1.1	1.0	0.4	0.5	0.6	0.8	0.4	0.8	0.0	0.2	0.3	0.0	0.1	0.1	0.2	0.3	0.1	0.1	0.2	0.0	0.1	0.1	0.1
-3.1	0.8		1.2	0.8	1.0	2.5	1.2	1.1	0.7	0.4	0.3	1.0	0.7	0.6	0.9	0.3	0.5	0.5	1.1	0.6	0.9	0.0	0.2	0.1	0.0	0.1	0.0	0.3	0.3	0.1	0.2	0.2	0.0	0.2	0.1	0.2
-3.2	0.7		0.9	1.3	0.7	1.2	0.9	0.9	0.9	0.4	0.3	0.6	0.7	0.5	0.8	0.3	0.5	0.4	1.5	0.8	0.6	0.0	0.2	0.0	0.0	0.1	0.0	0.3	0.2	0.0	0.3	0.2	0.0	0.1	0.1	0.1
-3.3	0.7		1.3	1.2	0.6	0.9	1.2	0.6	1.2	0.3	0.4	0.8	1.1	0.4	0.4	0.3	0.4	0.4	0.7	0.3	0.4	0.0	0.1	0.1	0.0	0.2	0.0	0.1	0.3	0.1	0.2	0.2	0.0	0.2	0.2	0.2
-3.4	0.4		0.7		0.4						0.3	0.3	0.8		0.7	0.6	0.4	0.4	0.9			0.2		0.1	-0.1	0.2	0.2	0.0	0.2	0.3	0.4	0.4	0.1	0.2	0.1	0.2
-3.5															0.7		0.4							0.0	0.0	0.3	0.3		0.2	0.2	0.0		0.1	0.1	0.2	0.1
-3.6																									-0.2		0.3		0.1					0.1	0.1	0.1
-3.7																																		0.1	0.2	0.1
-3.8																																		0.1	0.1	0.1
-3.9																																		-0.3	0.2	0.0
-4.0																																			0.2	

KENNISPROGRAMMA
NATTE KUNSTWERKEN

Comparison between PECT and laser measurements

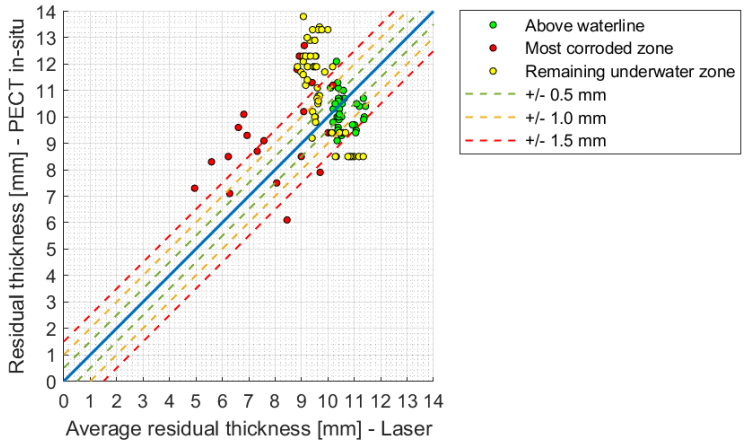
At each measuring point, the PECT measurement is compared with the laser measured residual thickness averaged over the surface of the PECT probe:

- SGS:
  - measurements in the lab: 45x45 mm
  - in-situ measurements:
    - above waterline: 45x45 mm
    - underwater: linearly varying between 45x45 mm and 120x120 mm at 4 m below the waterline
- RPS: 100x150 mm

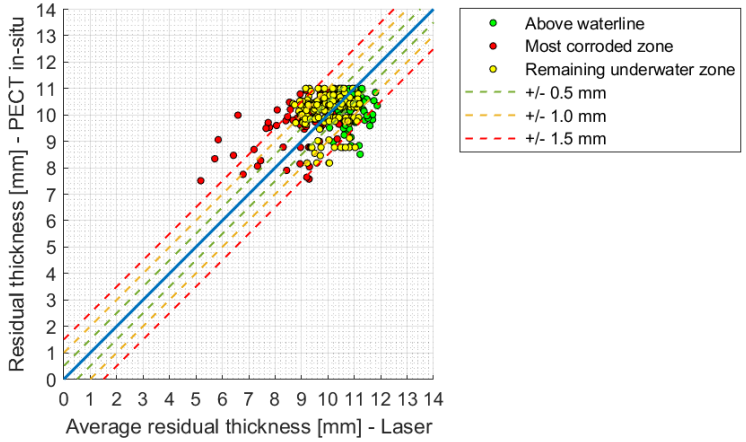
Comparison between PECT and laser measurements

In-situ measurements

Flanges – company 1

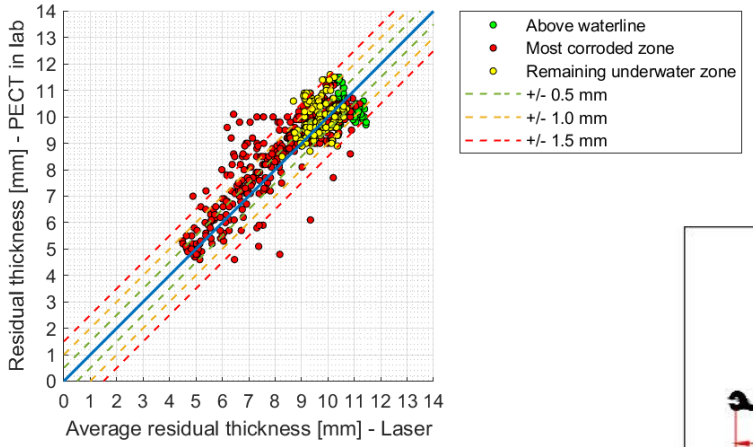


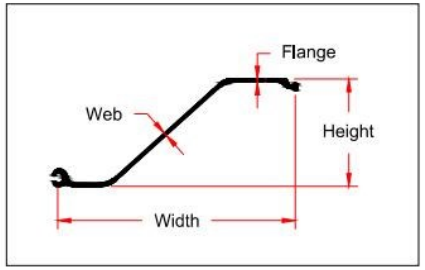
Flanges – company 2



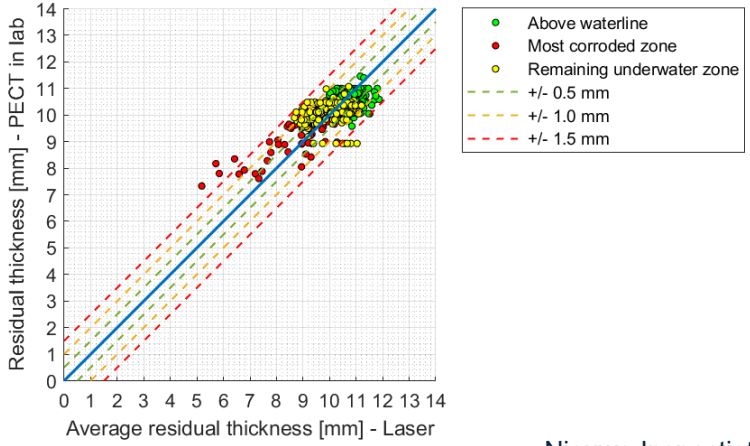
measurements in the lab

Flanges – company 1





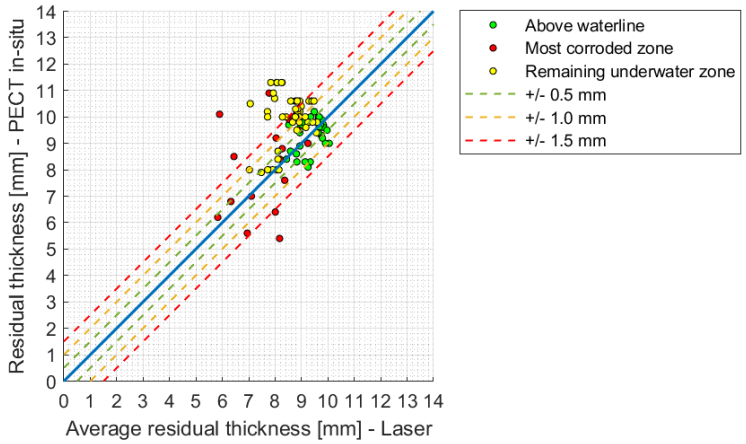
Flanges – company 2



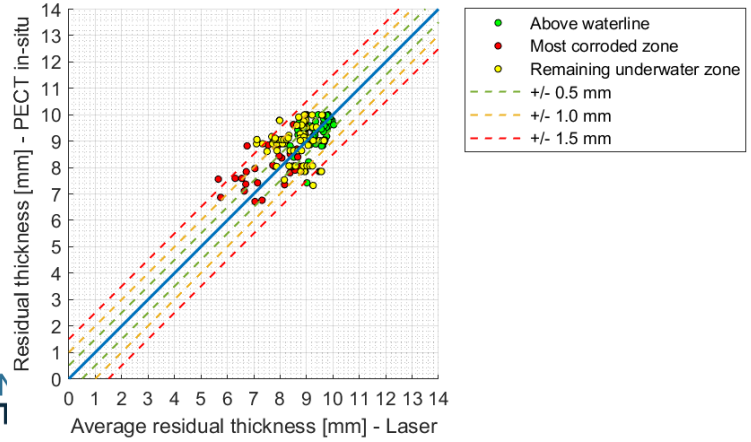
Comparison between PECT and laser measurements

In-situ measurements

Webs – company 1

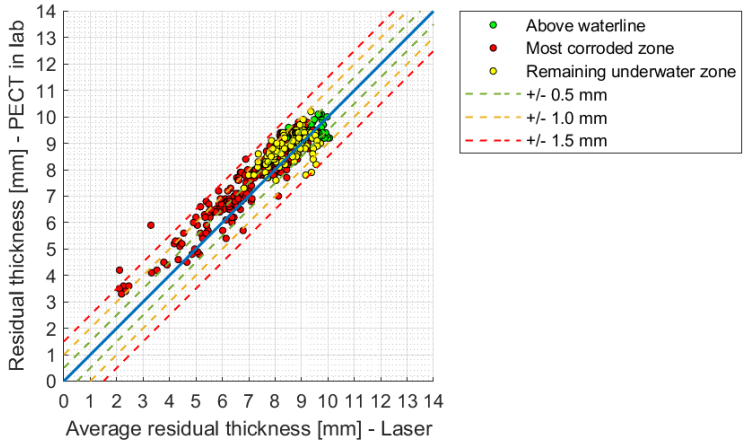


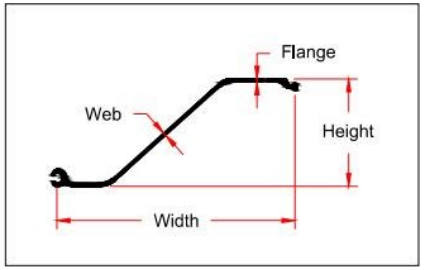
Webs – company 2



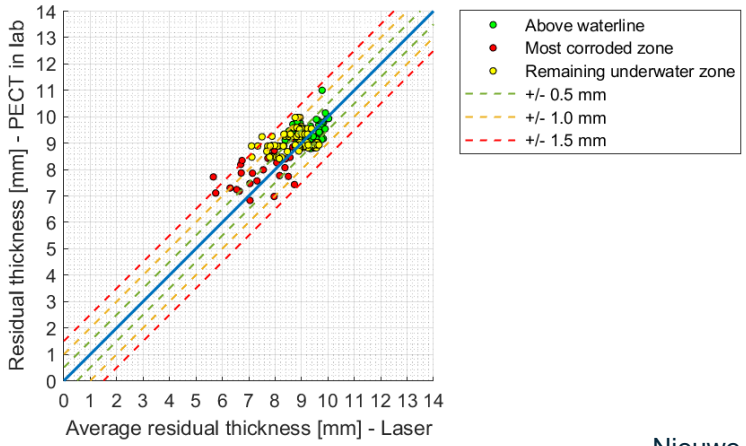
measurements in the lab

Webs – company 1

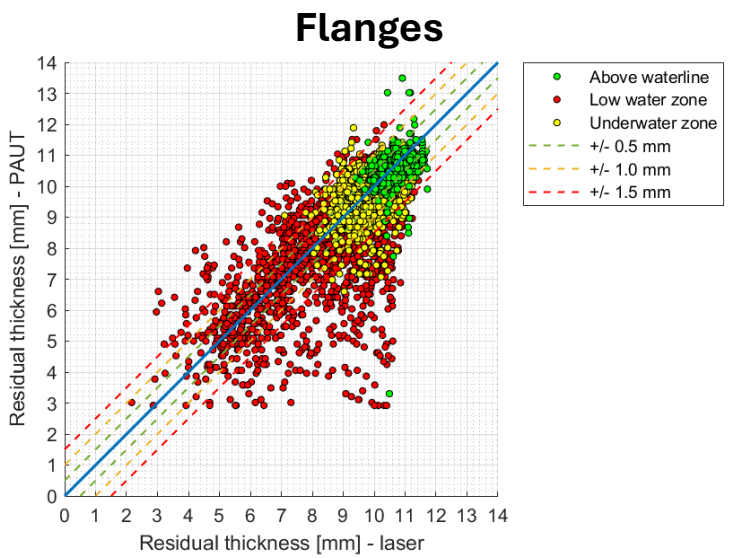


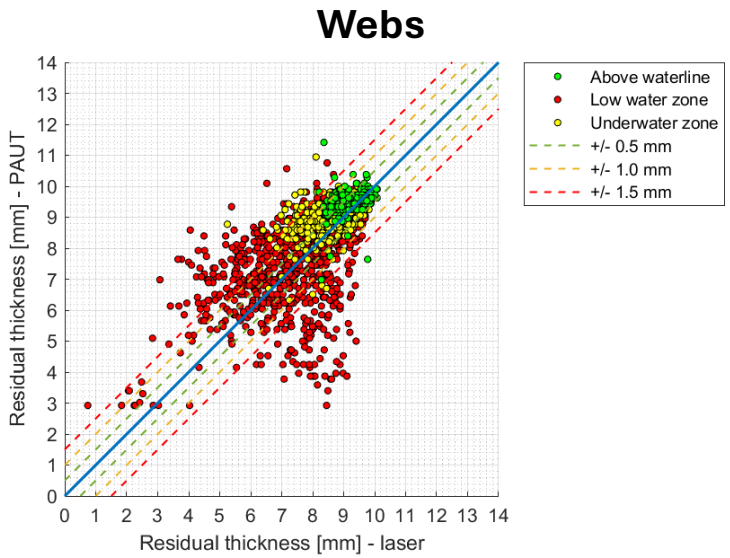


Webs – company 2

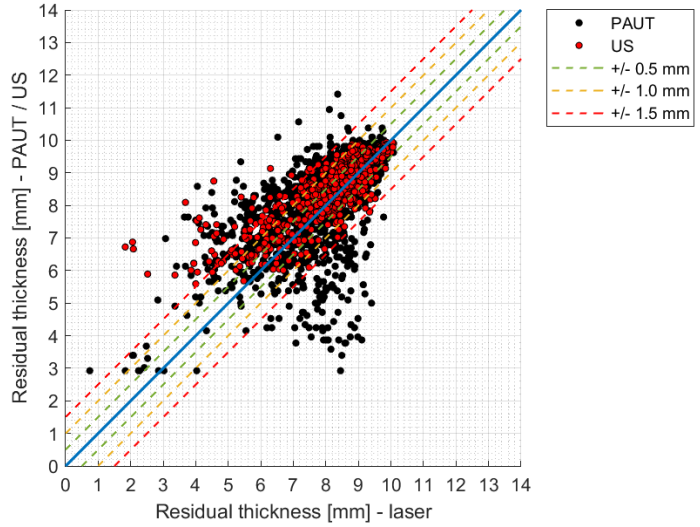


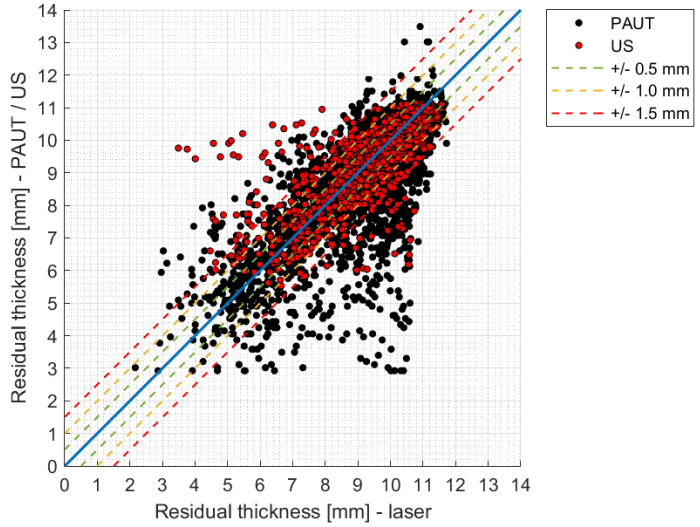
Comparison between PAUT and laser measurements



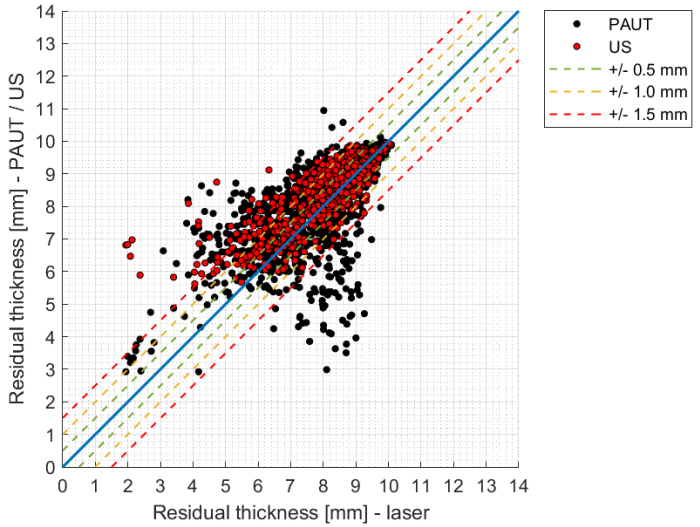


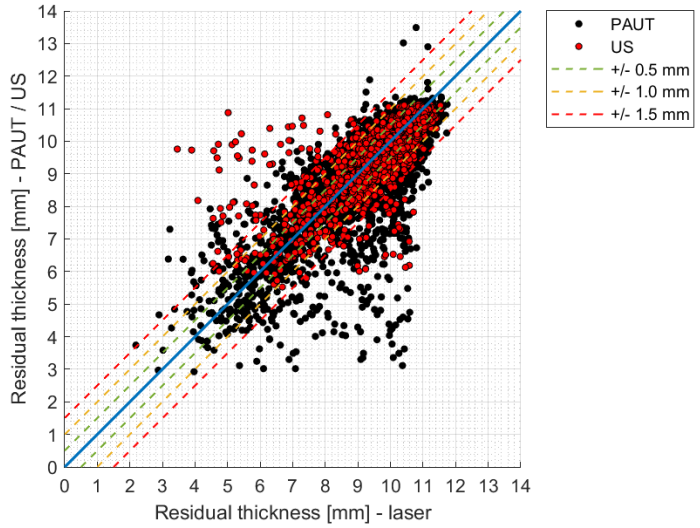
Comparison between PAUT, US and laser measurements





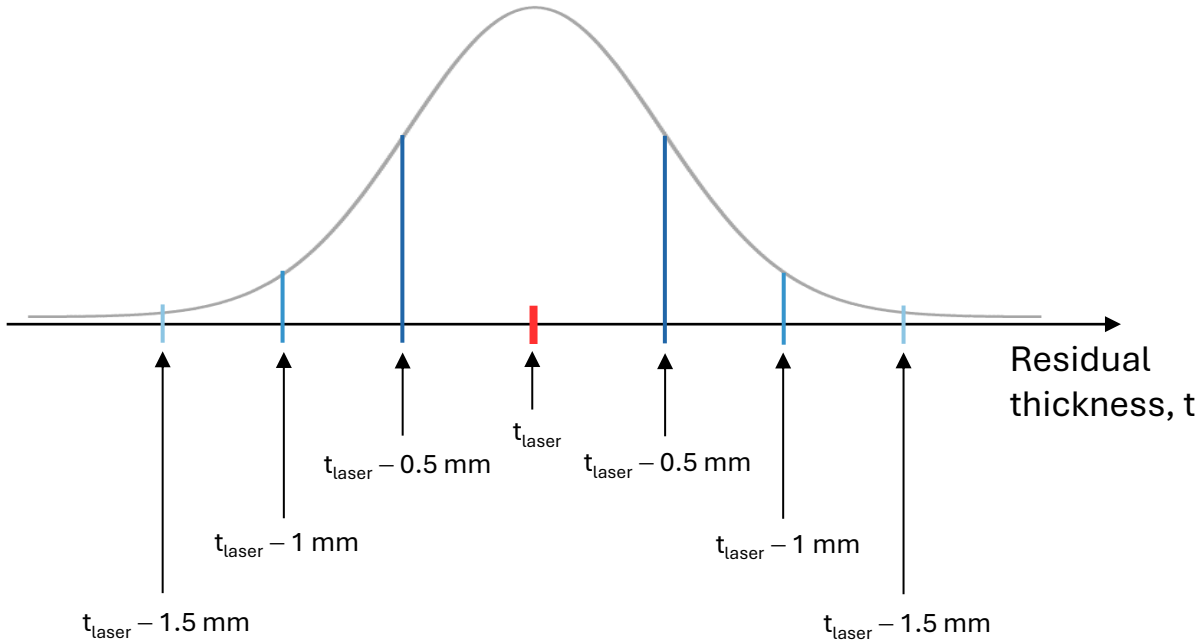
Pointwise comparison

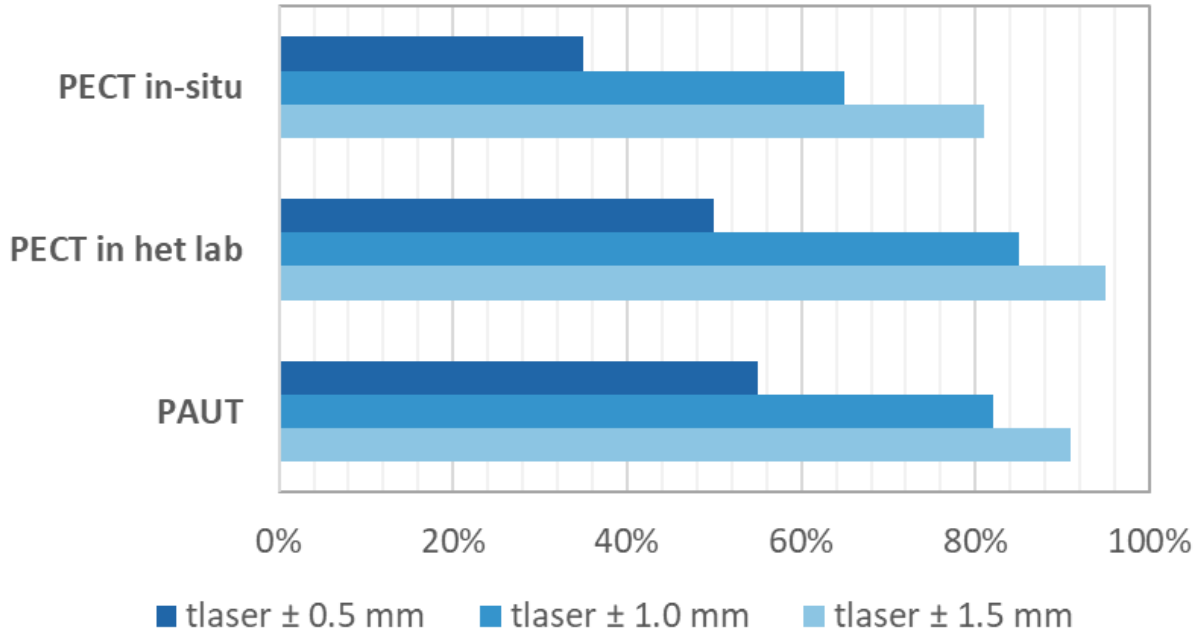




Comparison in terms of the **average thickness over 1 cm in depth direction**

Comparison between PECT and PAUT



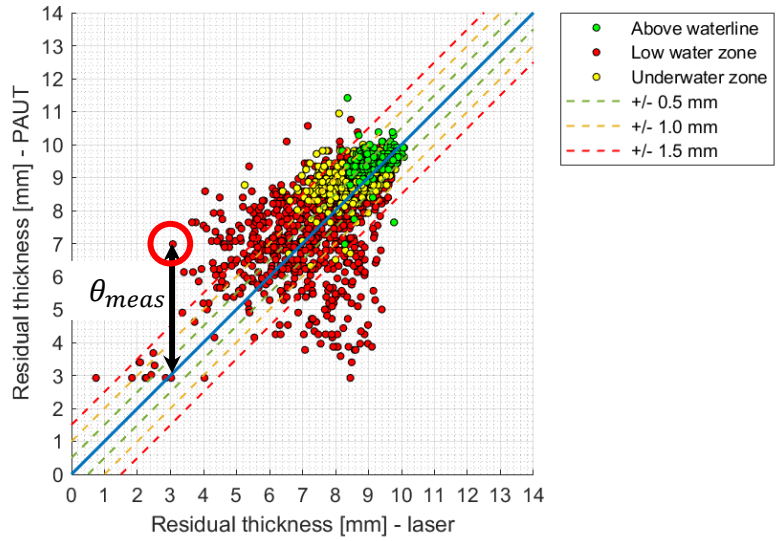


KENNISPROGRAMMA
NATTE KUNSTWERKEN

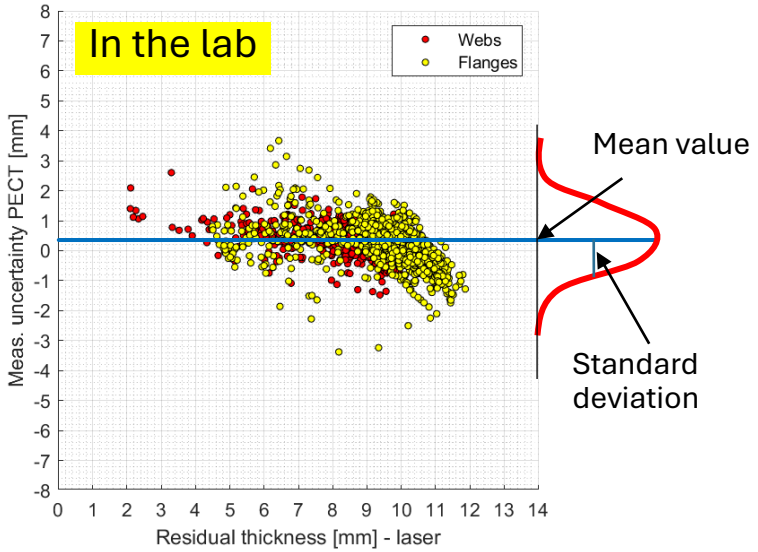
Measurement Uncertainty

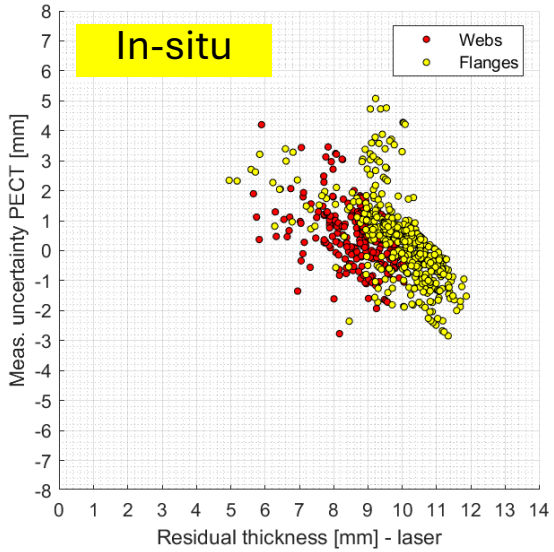
The measurement uncertainty is defined as:

$$\theta_{meas} = t_{PECT/PAUT} - t_{laser}$$



Measurement Uncertainty – PECT

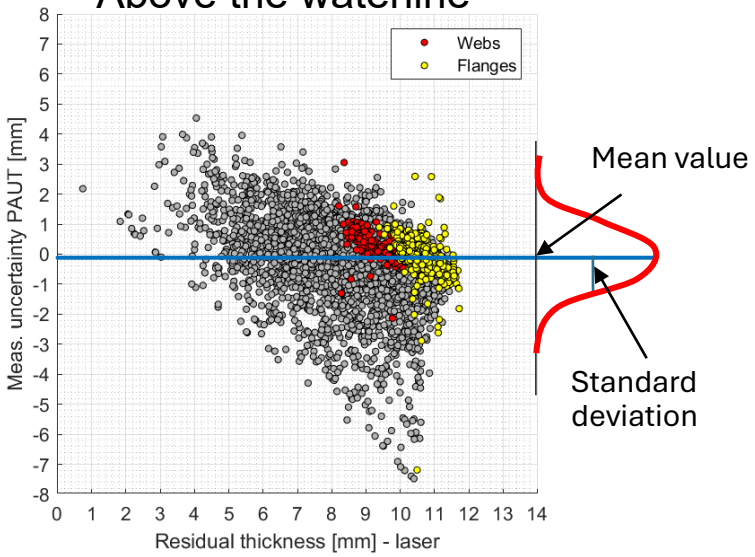




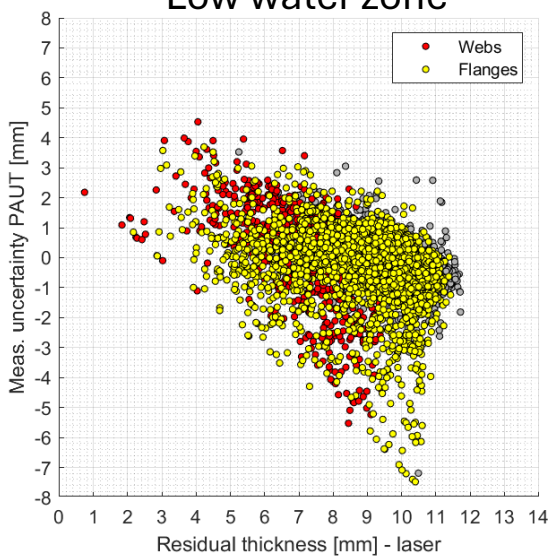
	Gem. waarde [mm]	Std. afwijking [mm]
PECT in-situ	0.35	1.25
PECT in het lab	0.23	0.70

Measurement Uncertainty – PAUT

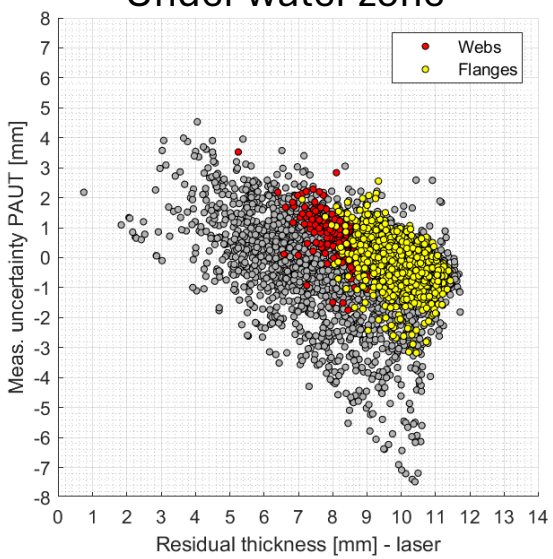
Above the waterline



Low water zone



Under water zone



Corrosion zone	Mean [mm]	Standard deviation [mm]
Above waterline	0.0	0.6
Low water zone	-0.2	1.3
Underwater zone	0.0	0.7
All zones	-0.1	1.1

KENNISPROGRAMMA
NATTE KUNSTWERKEN

Conclusions

- This study explored **alternative techniques** to traditional monitoring techniques for sheet pile inspection. Such as,
  - PECT eliminates the need for divers.
  - PAUT provides full-profile measurements.

- **90%** (PAUT), **81%** (PECT in-situ), and **95%** (PECT lab) of measurements align **within ±1.5 mm** of laser measurements. However, some errors can be significant and on the unsafe side (**overestimation** of the residual thickness).

- The accuracy of PECT measurements can be **significantly** affected by the external conditions during the measurements (in-situ vs. lab conditions).

- The analysis of PAUT concerns measurement performed in the laboratory (**“ideal” conditions**). Additional factors may influence the measurement uncertainty in the field.

Suggestions

To our best knowledge, there are no similar studies in the literature:

- For PECT, a second measurement campaign is strongly recommended, using the lessons learned from this one.
- The **calibration** of the measurement devices should be improved.
- The use of the measurements **including their uncertainty** for the **safety assessment** of existing structures should be further clarified and standardized.
- A **measurement protocol** needs to be developed for PECT with requirements and recommendations aiming to limit the effect of the in-situ conditions on the accuracy of the measurements for sheet piles.

- Feel free to contact us to **determine measurement strategies**, including locations, quantity, and appropriate monitoring techniques based on asset-specific conditions.

Het kennisprogramma loopt door !

Interesse of meedoen?

Bezoek nattekunstwerkenvandetoekomst.nl/meedoen

Rapporten:

https://www.nattekunstwerkenvandetoekomst.nl/kennisbank/

Deltares

MARIN

Rijkswaterstaat
Ministerie van Infrastructuur en Waterstaat

TNO innovation for life

Ece Ozer : ece.ozer@tno.nl
Diego Allaix : diego.allaix@tno.nl

KENNISPROGRAMMA
NATTE KUNSTWERKEN