Smart quay walls & trends in quay-wall engineering

Alfred Roubos

Stufib Ledenvergadering - Innovaties in kademuren
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Rotterdam, The Netherlands

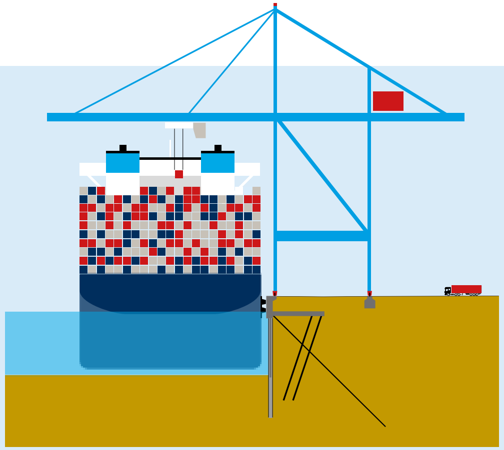
Introduction: Alfred Roubos

- Port Engineer (≈ 17.5 years)
- Researcher Delft University of Technology (Doctoral defence 2019)
- Member of national & international committees (Eurocode CEN/NEN, CROW, PIANC, BS)

Main research focus:

- Marine structures (e.g. quay walls, jetties, dolphins)
- Dredging, scour protection
- Innovations & full-scale field tests

PhD: reliability of quay walls

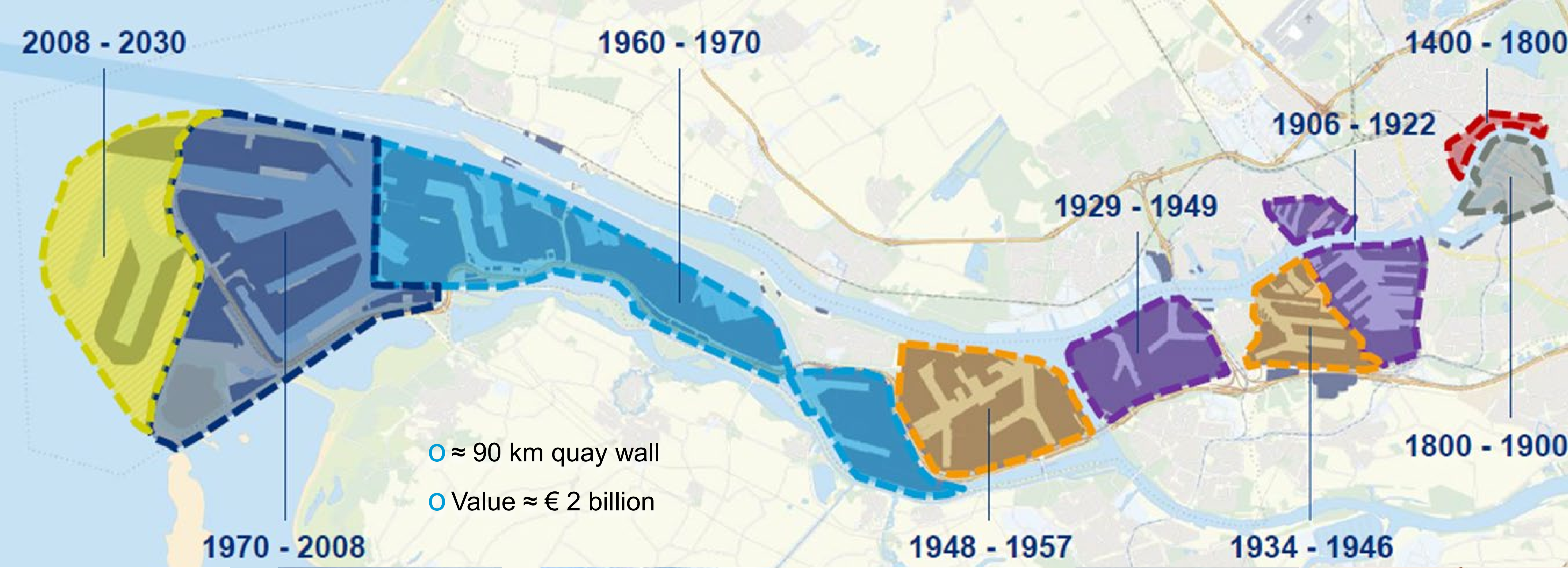


Full scale field test foundation piles

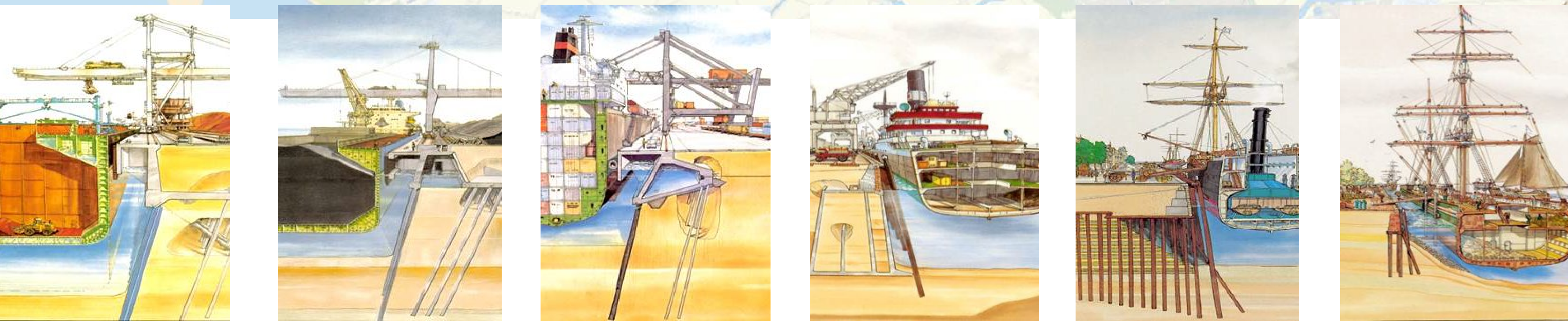
Bow-thruster induced scour

Content

- Introduction
- Trends in quay wall engineering (PoR)



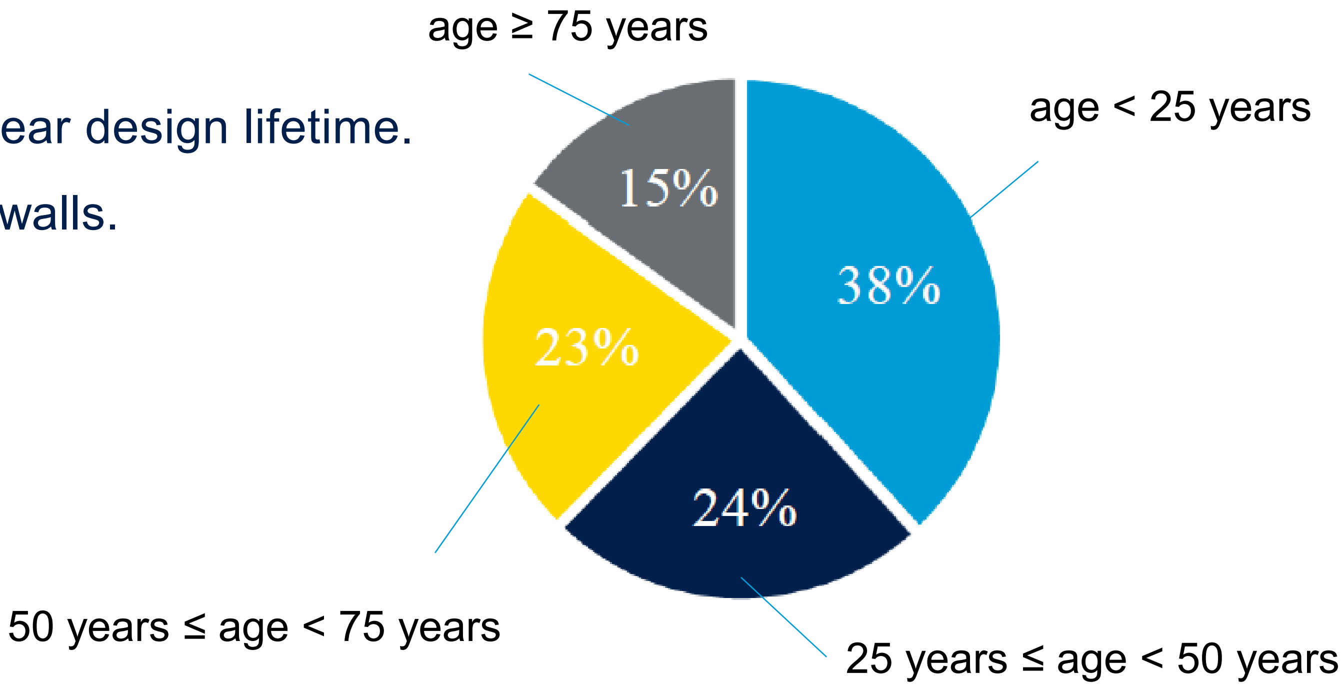
- ≈ 90 km quay wall
- Value ≈ € 2 billion

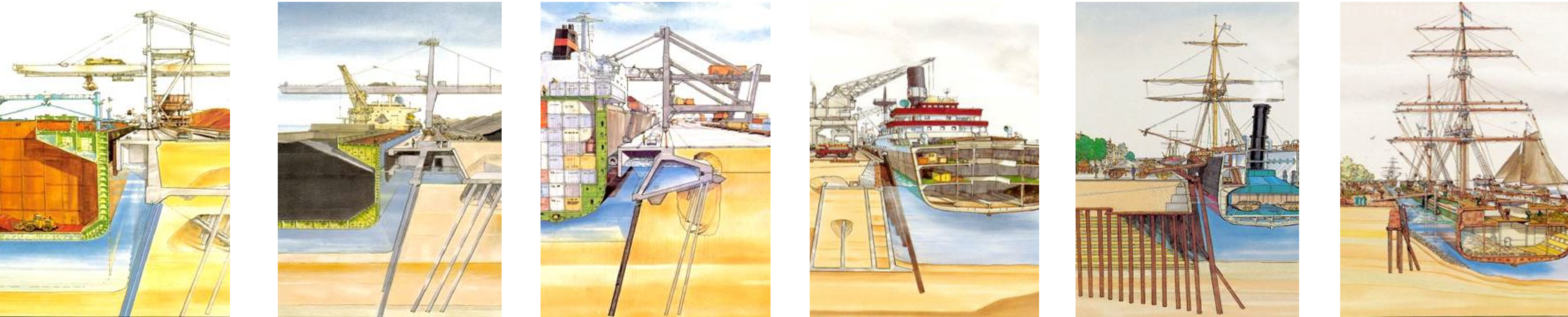


Situation in Rotterdam

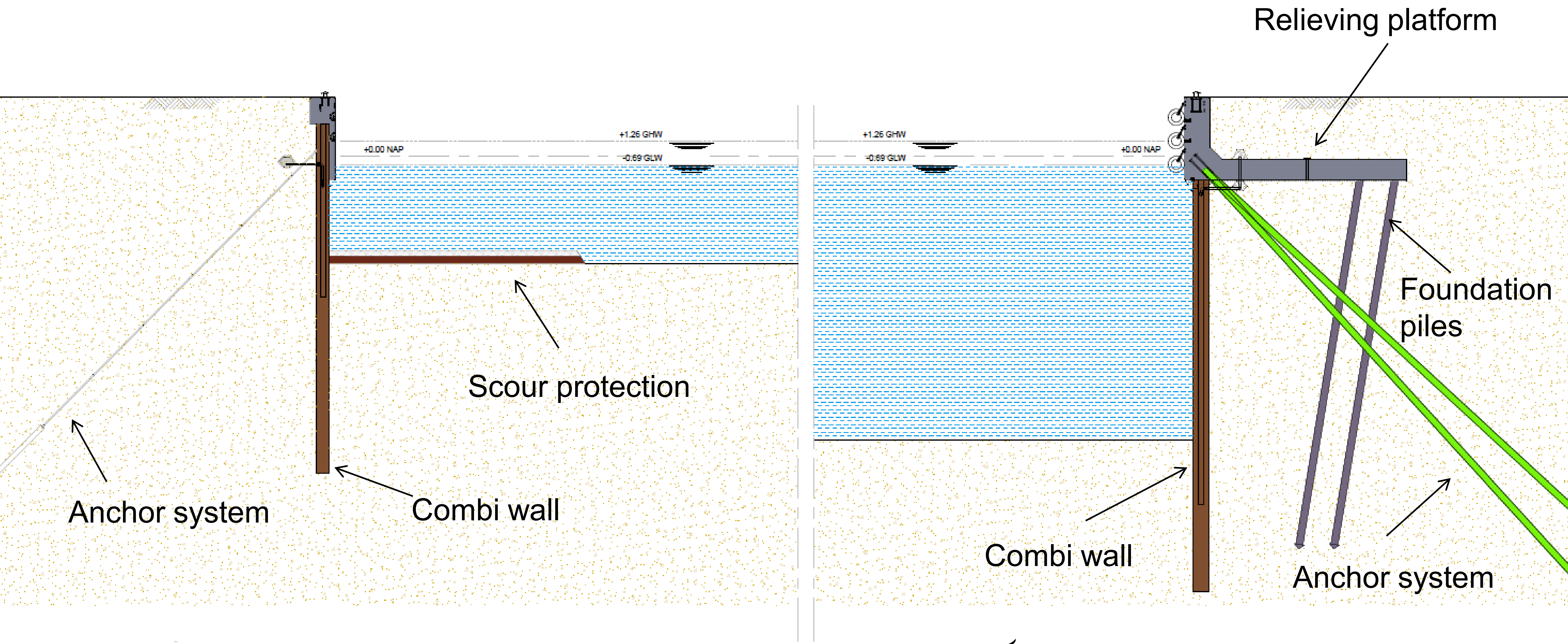
- Many quay walls approach the end of their fifty-year design lifetime.
- Focus will shift towards assessing existing quay walls.
- Most quay walls are in good condition.

⟹ Not yet the end of their service life!

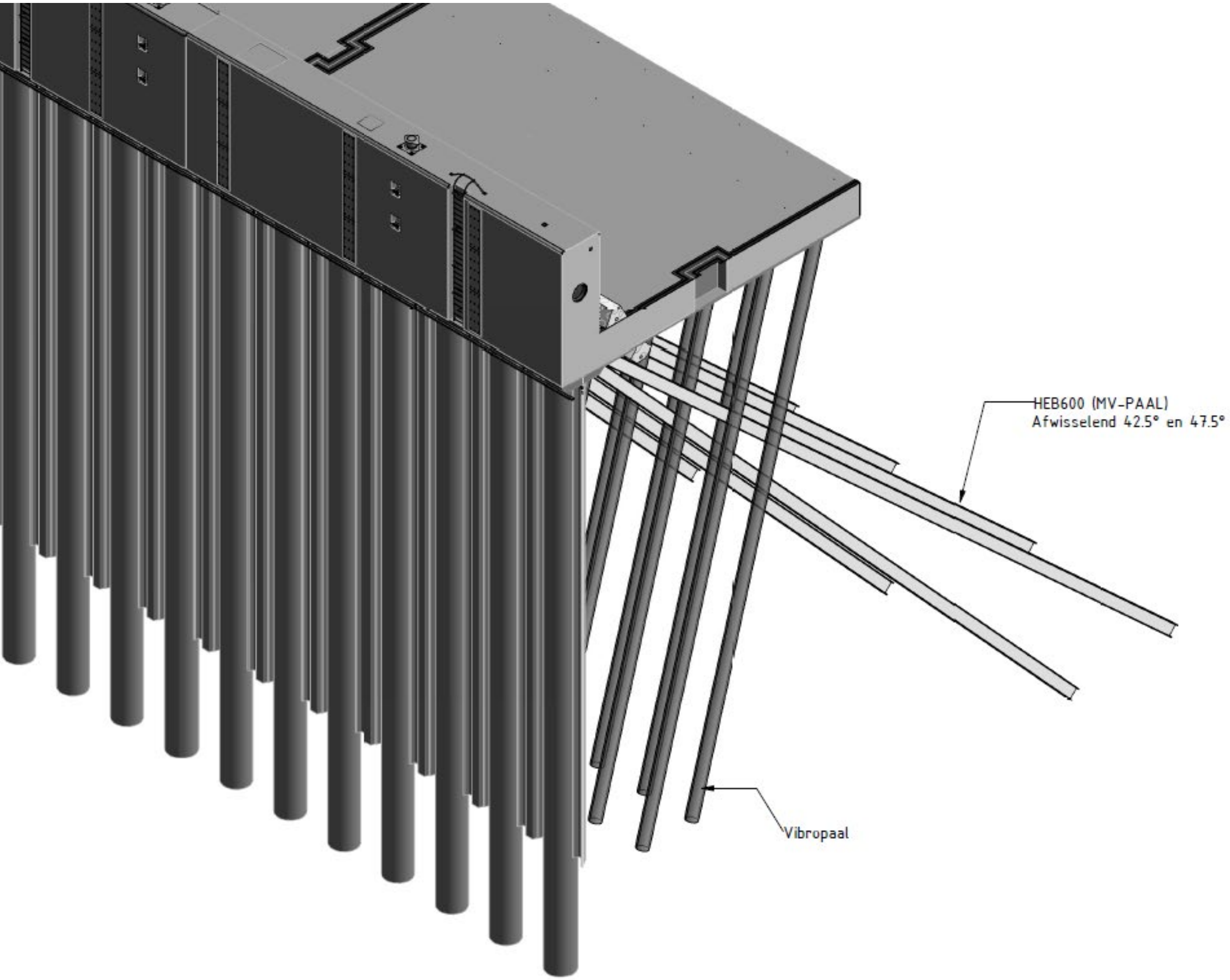


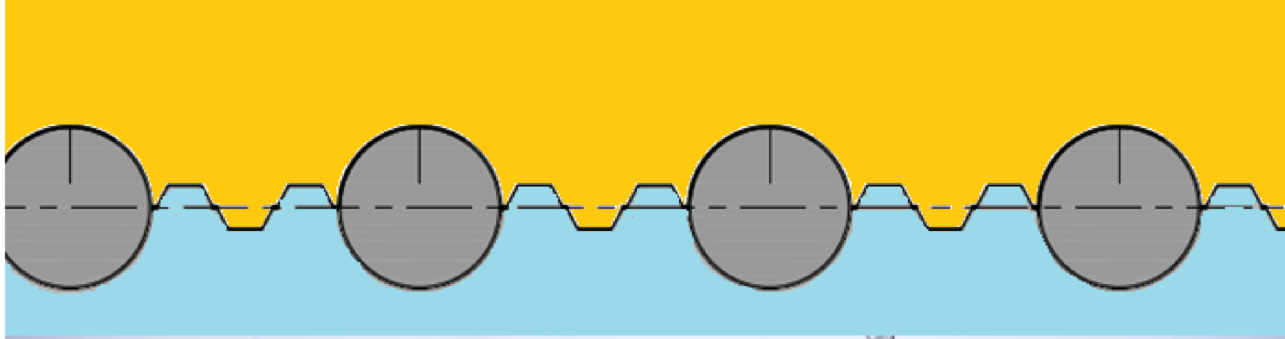


Standard quay-wall design solutions



Typical combi wall



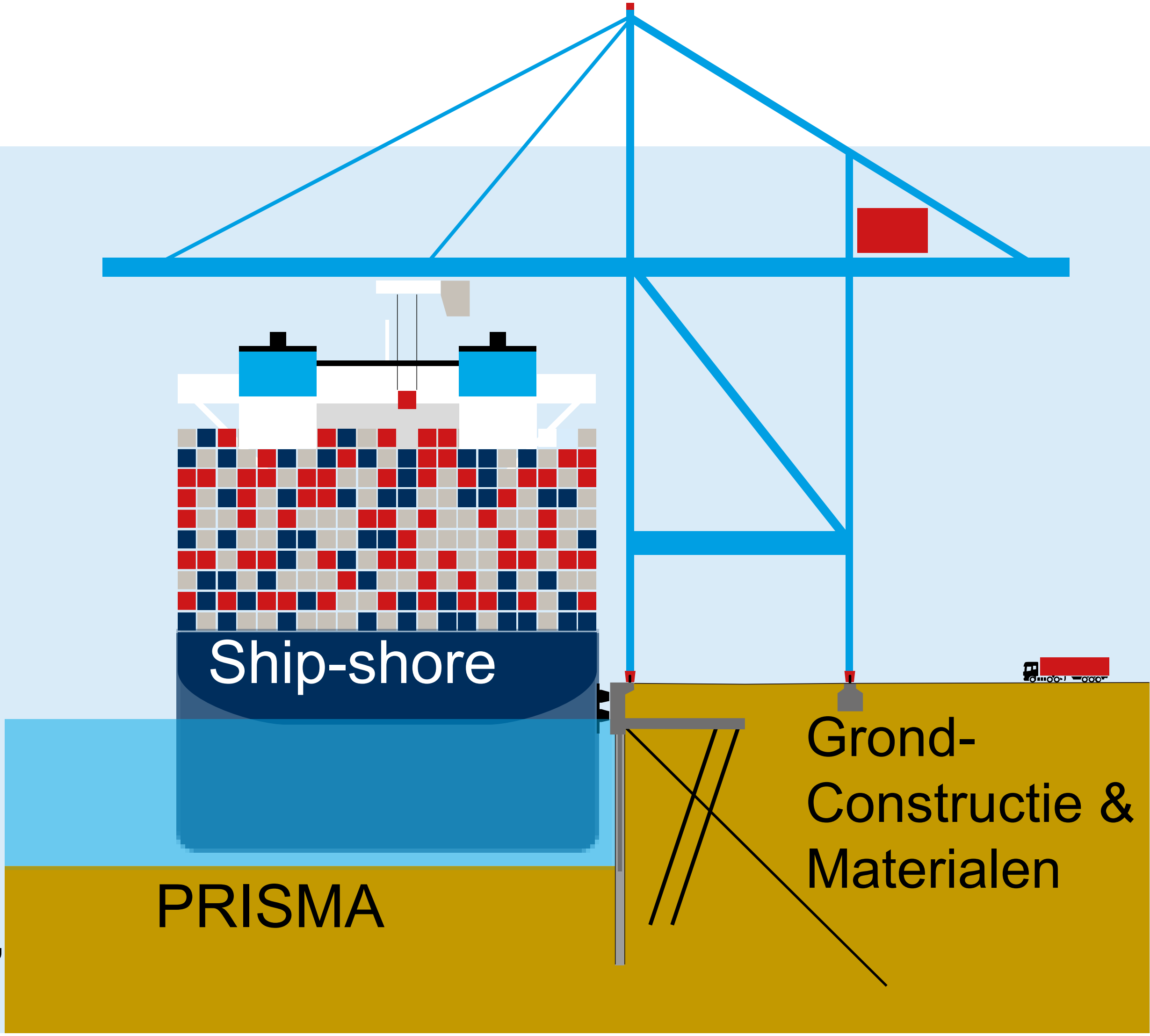


Typical combi wall

Infra Innovation: Grond-Constructie-Materialen

Main aim towards 2030:

- Lifetime extension quay walls (≥ 25 years)
- Optimise performance of existing port infrastructure* by facilitating modern vessels (e.g. larger nautical draft / bigger cranes).
- A significant contribution to CO_2 reduction of using less or carbon friendly materials, without compromising safety/reliability of new port infrastructure*.
- Development of future-proof port infrastructure* (e.g. robust, adaptive, upgradeable, flexible)
- Transition towards climate resilient port infra structure* (e.g. implementation of circular, modular, nature-inclusive, nature-based design solutions)



*) Quay walls, jetties and Flexible dolphins

**) Reduction of CO_2 emissions during construction is not the main aim of GCM.

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GROND— CONSTRUCTIE – MATERIALEN

Impact van innovatie op de haven, 2018-2022

Projecten met toegepaste innovaties, 2018-2022

Agrofood
Amaliahaven
Antarcticakade
Calandkanaal (palen)
Dordrecht
ECT
EECV
HHTT
Rhenus
Rosilcokade EBS
Rozenburgse Sluis
SIF1
SIF2
Kade Shell
Steigers Neste (vmlg BLC)
Vopak

Project: Aanpassen scheurwijdte criterium
Impact: -€2,5 mln, -1,75 kton CO_2
- **Gerealiseerd: SIF2**
- **In voorbereiding/uitvoering: Amaliahaven**
- **Aangetoond (nog toe te passen): Onderdeel RE**

Project: CC klasses
Impact: -€5 mln, -7,5 kton CO_2
- **Gerealiseerd: HHTT, SIF2,**
- **In voorbereiding/uitvoering: Amaliahaven, Antarcticakade**
- **Aangetoond (nog toe te passen): Agrofood**

Project: Paalproef Maasvlakte
Impact: -€15,5 mln, -11 kton CO_2
- **Gerealiseerd: SIF2, ECT**
- **In voorbereiding/uitvoering: Amaliahaven, ECT**
- **Aangetoond (nog toe te passen): Onderdeel RE**

Project: Reverse Engineering (combinatie van I² projecten)
Impact: 20-50% meer belasting, verlengen levensduur EN/OF verdiepen ligplaats met 1 a 2m
- **Gerealiseerd: EECV, ECT, Dordrecht, Rosilcokade EBS, SIF1, SIF2, Vopak**
- **In voorbereiding/uitvoering: ECT, Neste steiger, Rozenburgse Sluis**
- **Aangetoond (nog toe te passen): HHTT, Rhenus**

Project: Onderzoek schroefstraalbelasting
Impact: -€0,5 mln, -0,45 kton CO_2
- **Gerealiseerd: HHTT**
- **In voorbereiding/uitvoering: Antarctikakade, Shell**
- **Aangetoond (nog toe te passen): Onderdeel RE**

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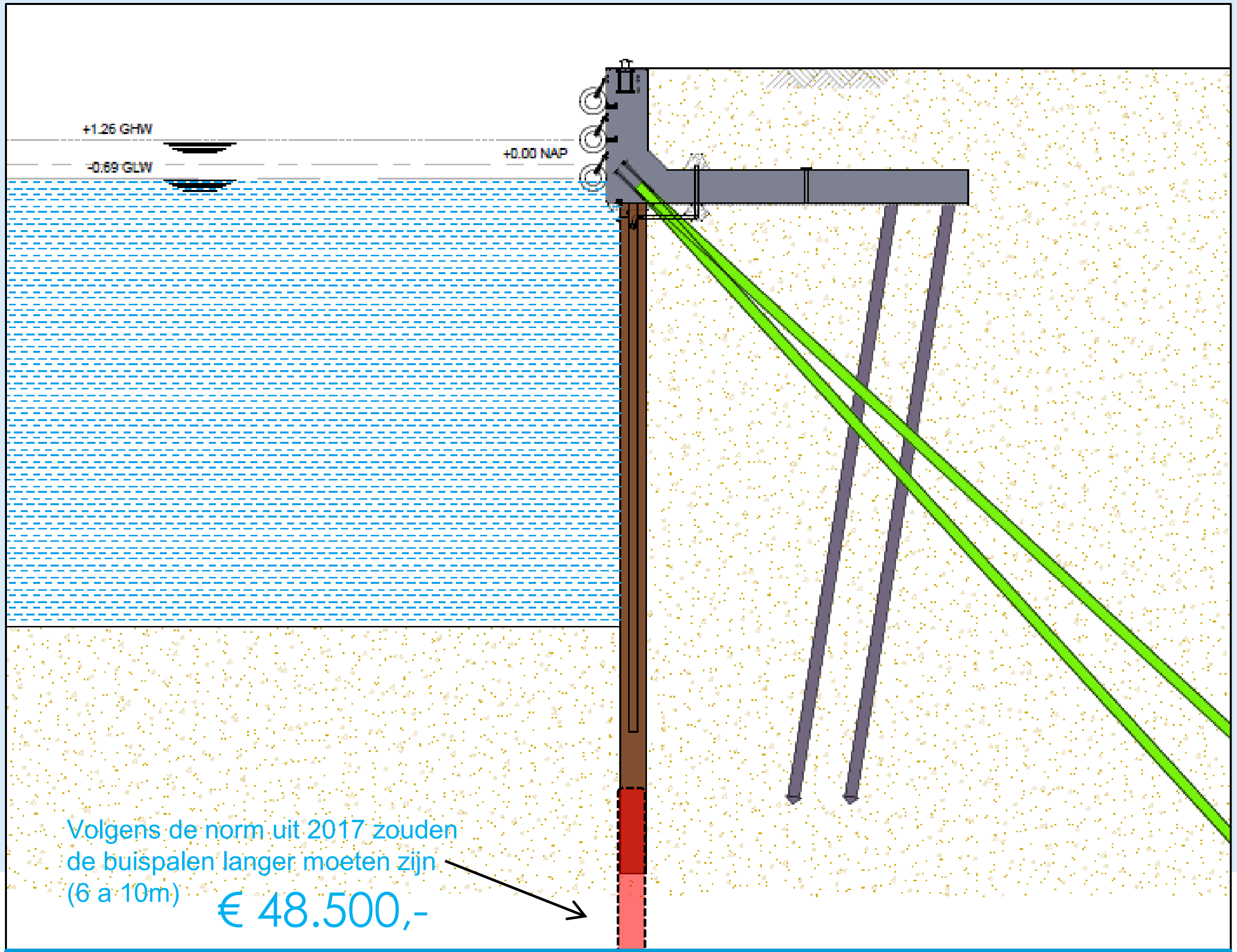
GROND – CONSTRUCTIE – MATERIALEN

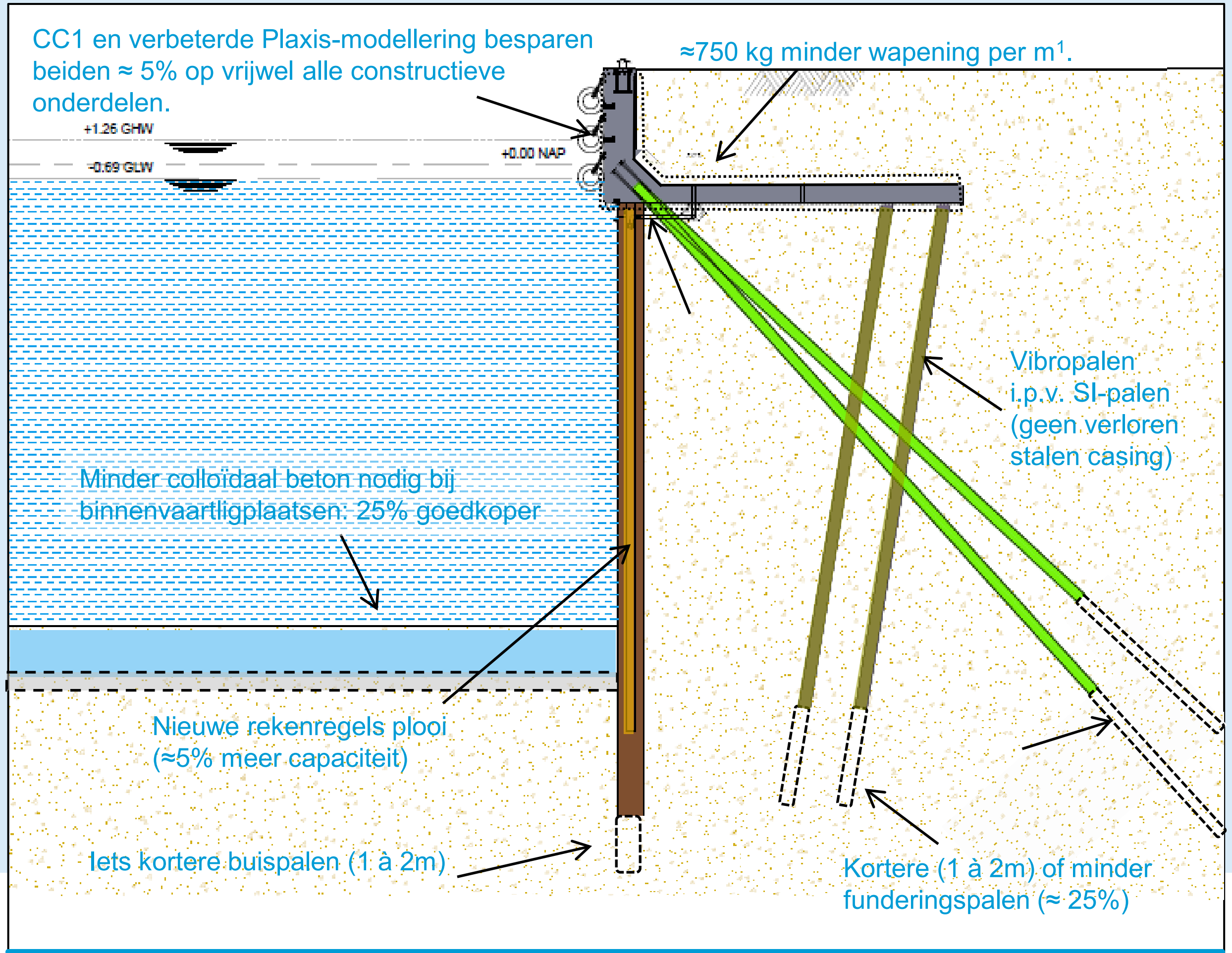
VERGELIJKING 2018-2023, PER STREKKENDE METER KADEMUUR (OP BASIS VAN DEEPSEA KADE HHTT)

2018) Directe bouwkosten: € 46.250,- / Emissie CO_2: 78 *ton***



Deepsea kade 2018

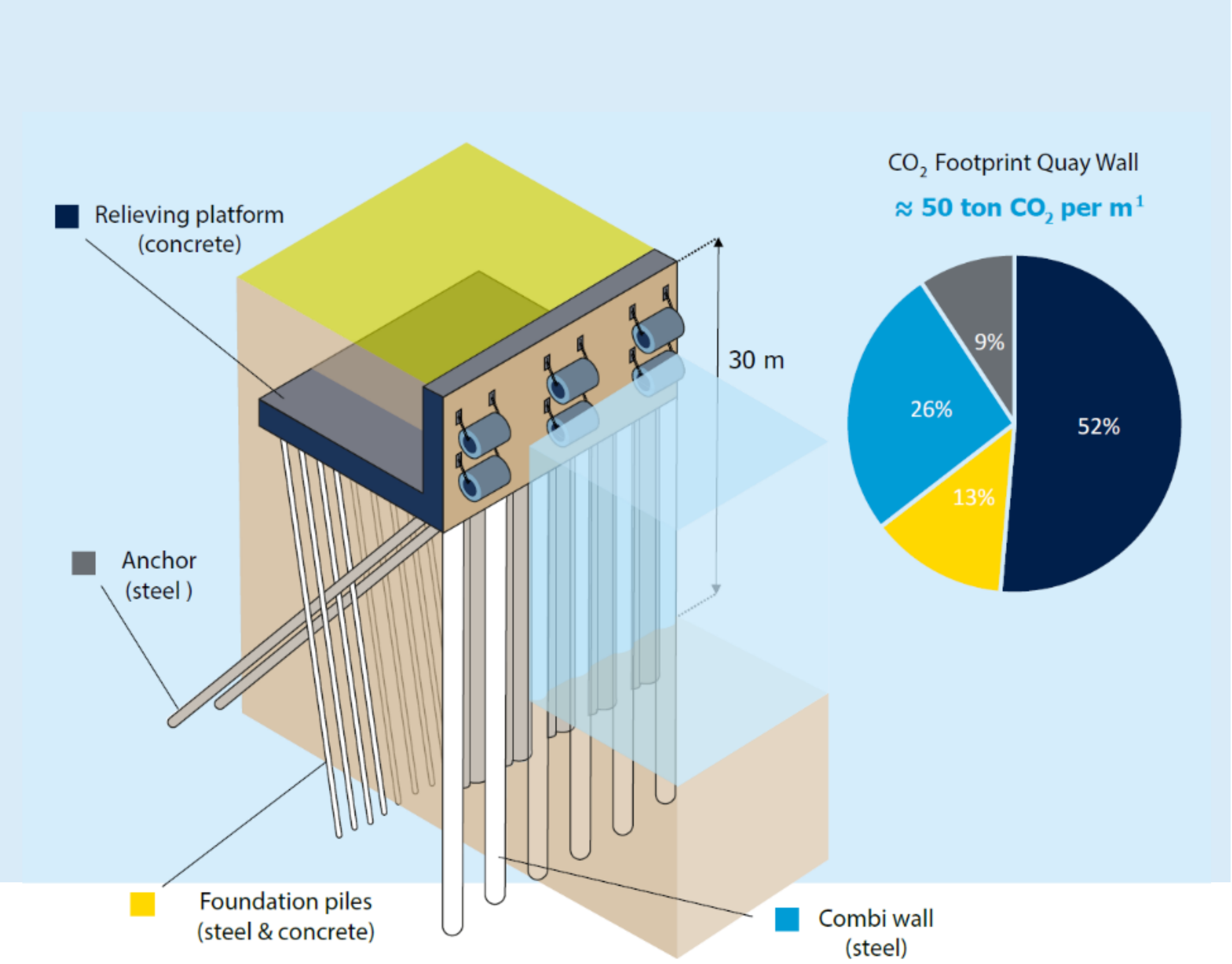
2023) Bouwkosten : € 39.500,-*/ Emissie CO_2: 65 ton**

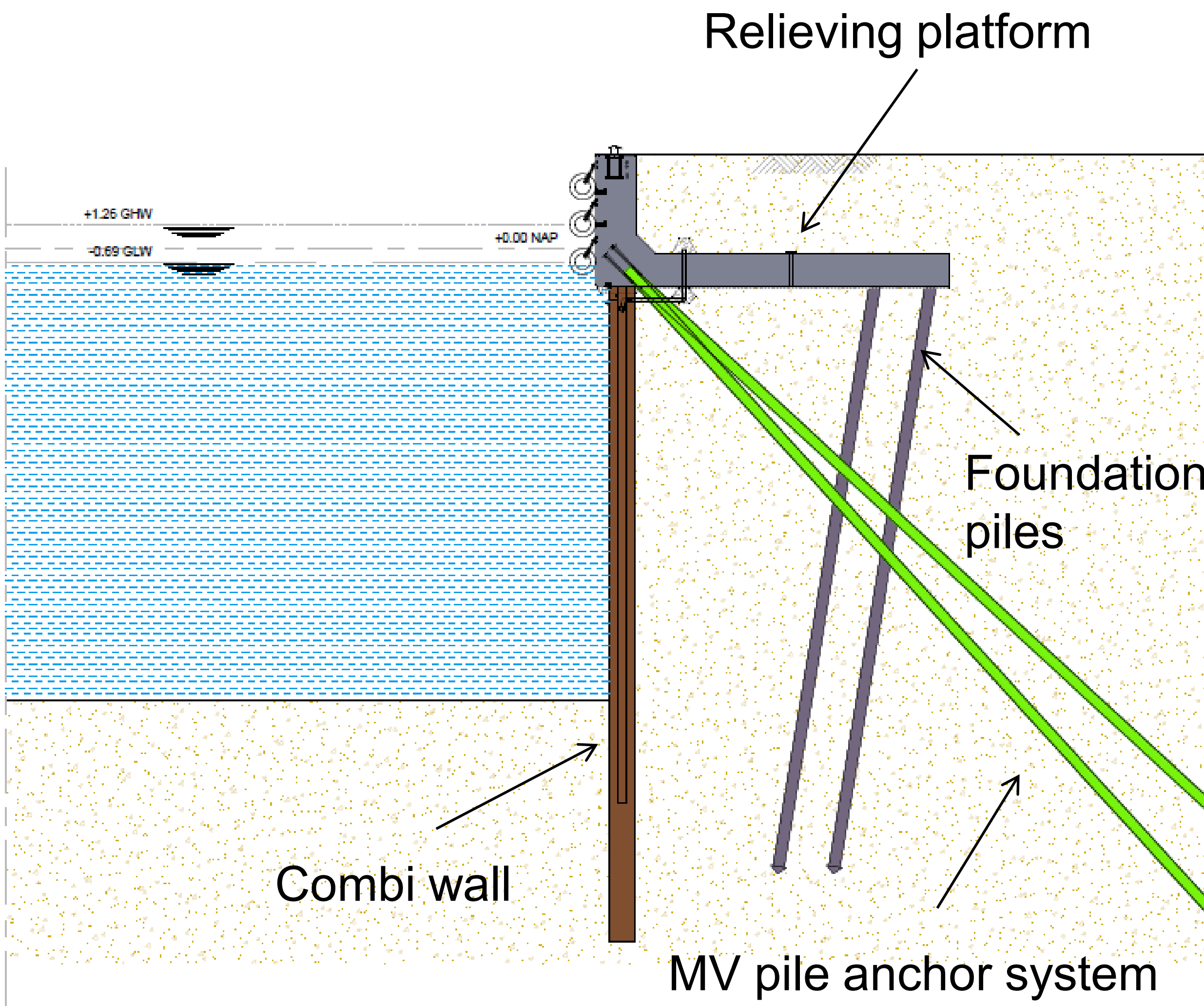


Deepsea kade 2023: Belangrijkste gerealiseerde optimalisaties

*) Vergelijking is gebaseerd op basis prijspeil 2017
**) Gebaseerd op rekenmethode anno 2023

Decarbonisation ≈50% before 2030 and 95% before 2050





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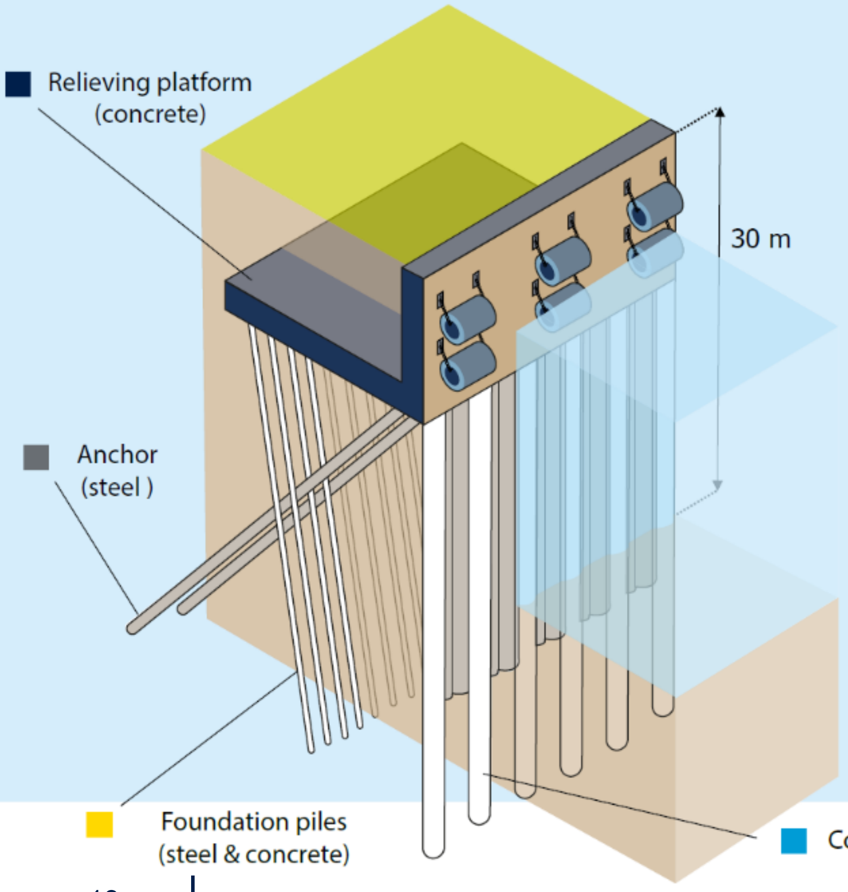
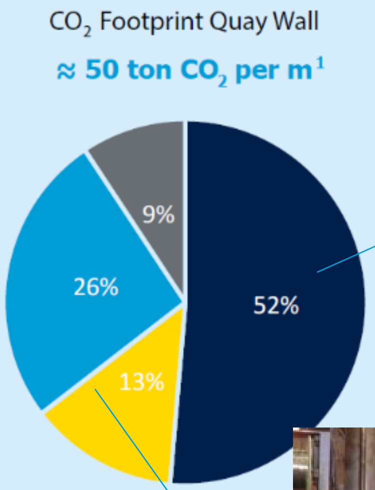
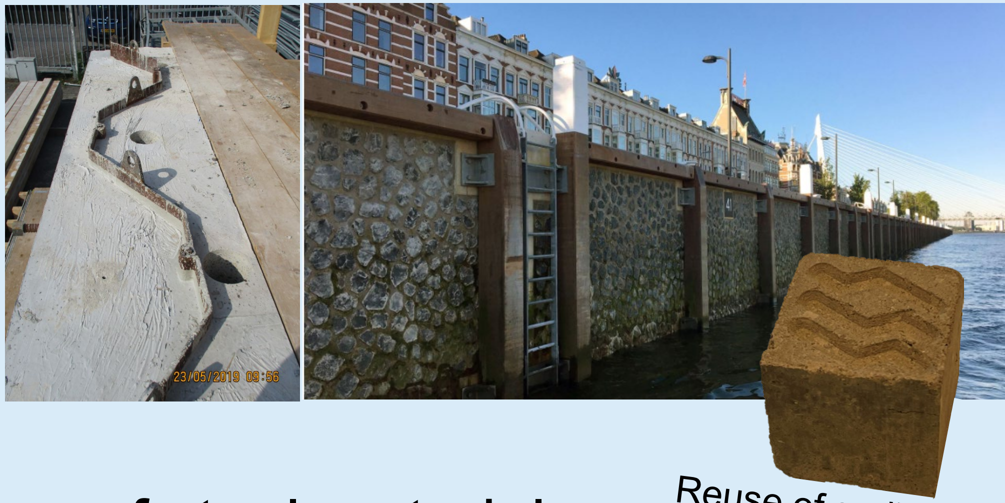




New types of concrete



Reuse of sediment

Optimal use of steel materials

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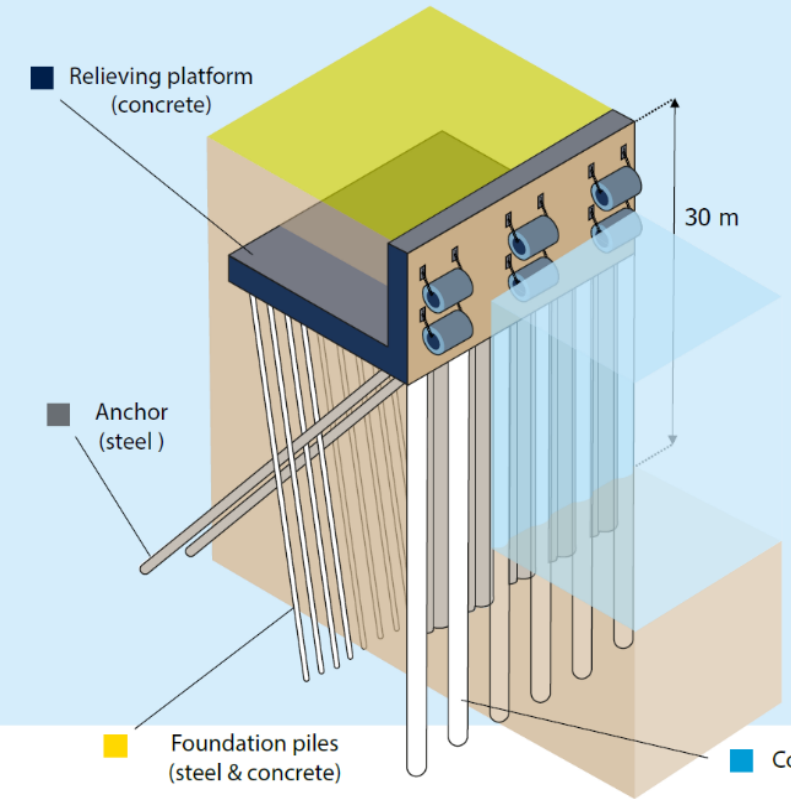
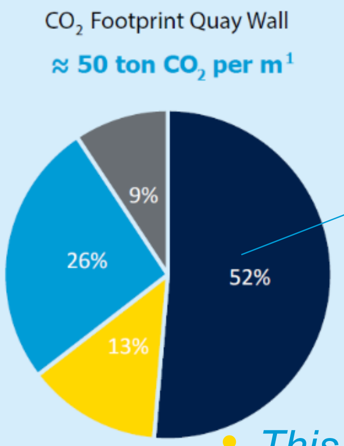
Vision & Ambition
Connecting the world. Building tomorrow's sustainable port.

Geopolymer concrete

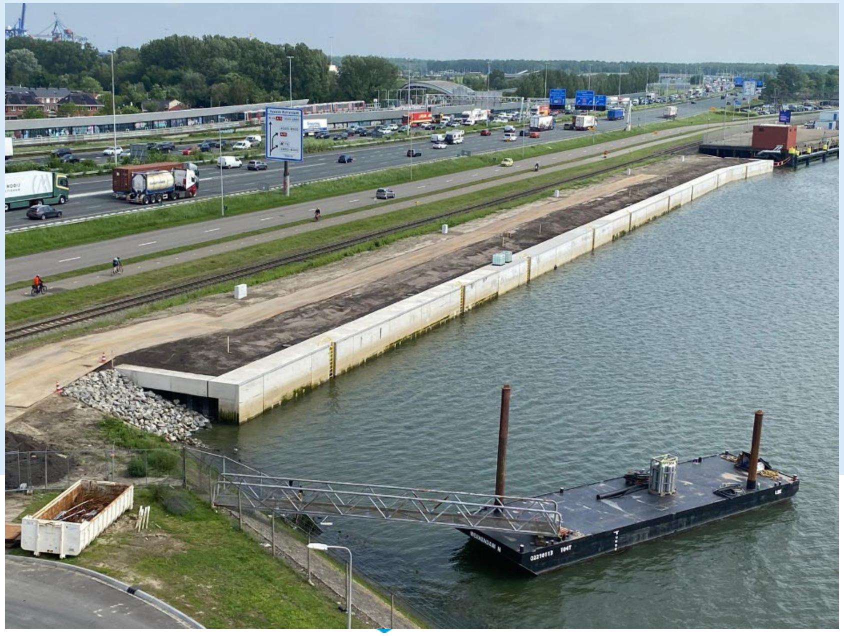
Existing structures

- Lifetime extension and optimize/maintain functionality.





- *This results in approximately 50 % CO_2 reduction in quay wall 2e Petreoleumhaven*



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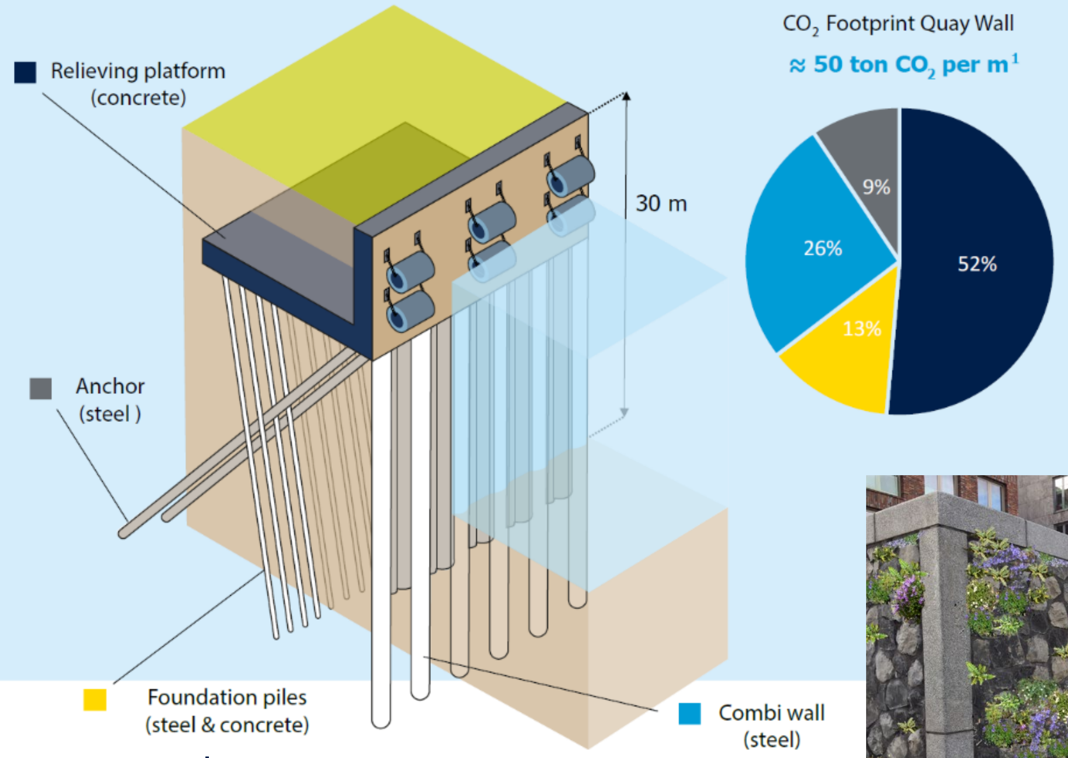
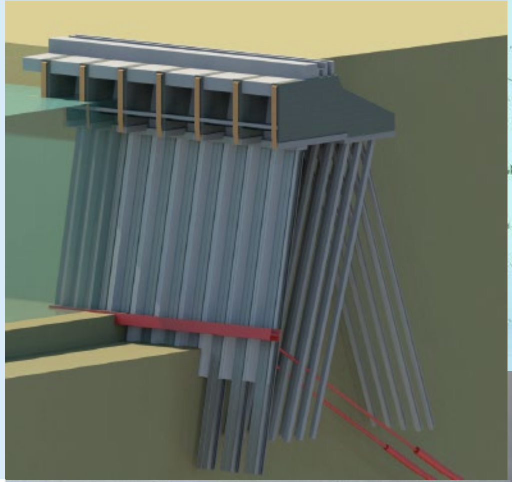
Existing structures

- Lifetime extension and optimize/maintain functionality.
- > 1500km soil retaining walls (Netherlands)

New marine structures

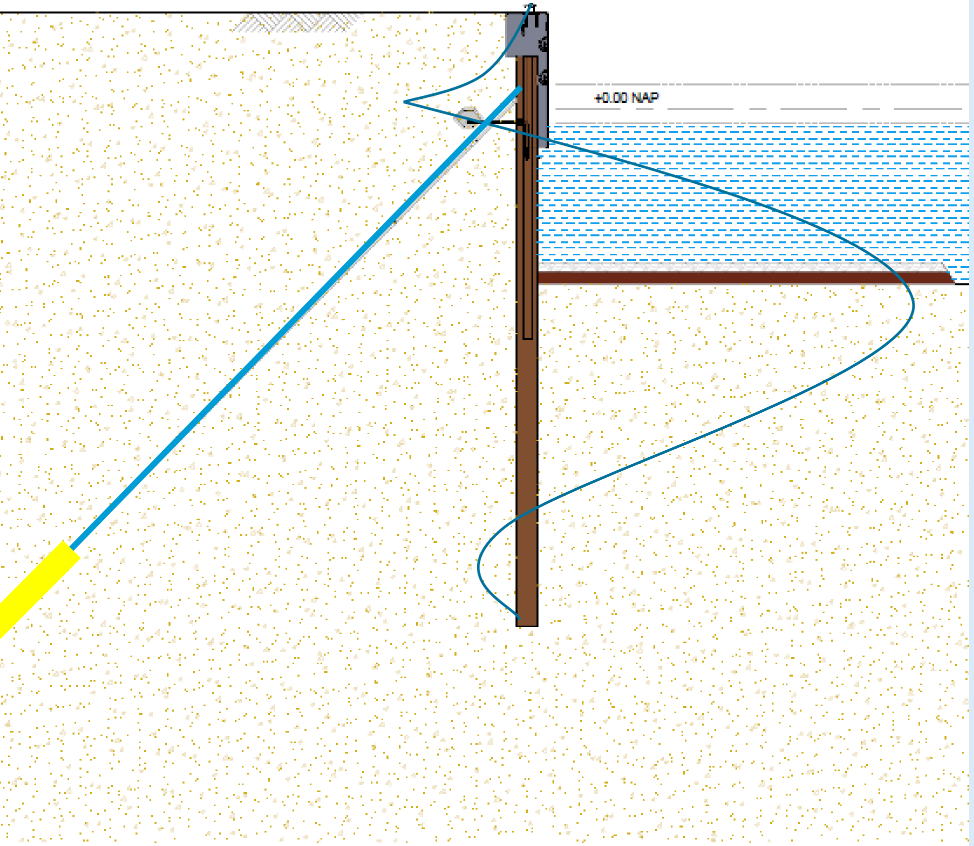
- 2023 - @2035@ => **Upgradeable / adaptive**
- @2035@ - 2050 => **Circular / modular / “green”**





First under water anchors in Rotterdam

Key principle



Lifetime extension existing quay walls

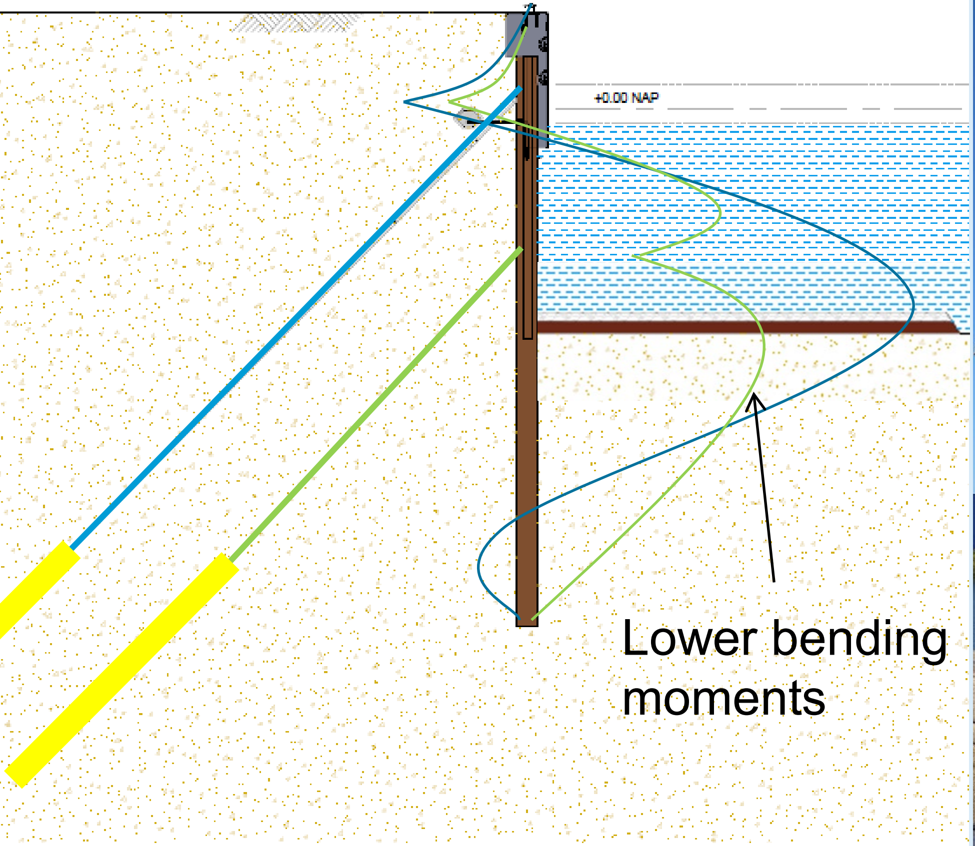
- Compensate effects of corrosion.
- Increase functionality (deepening or higher load)

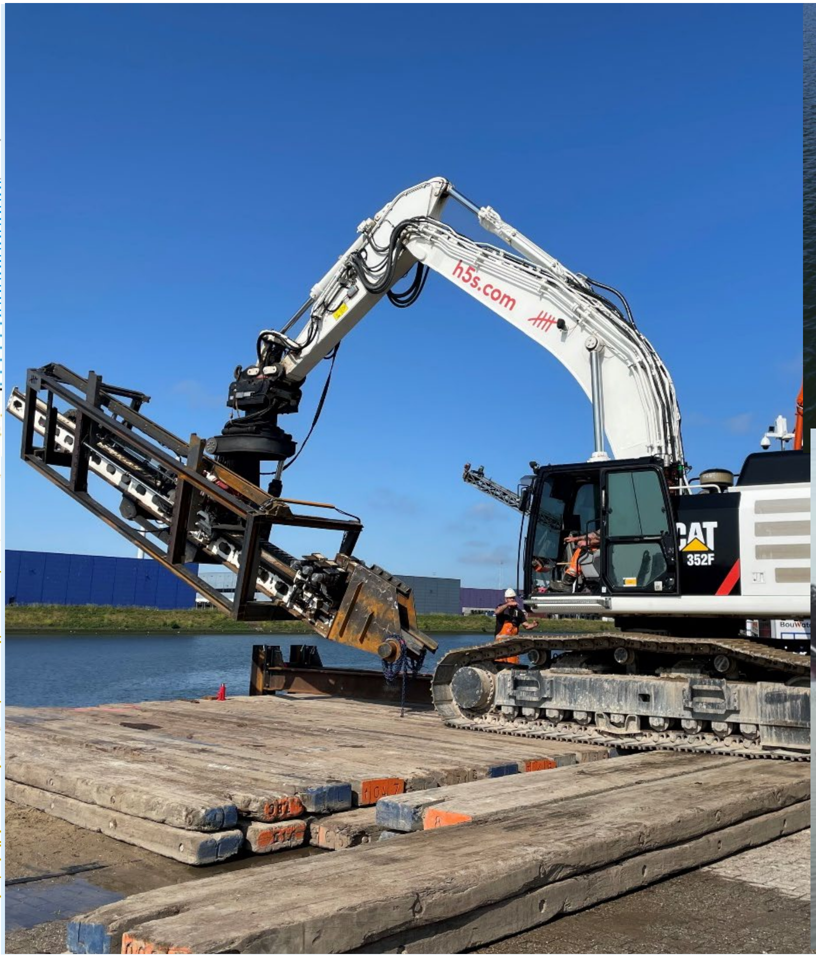
OR

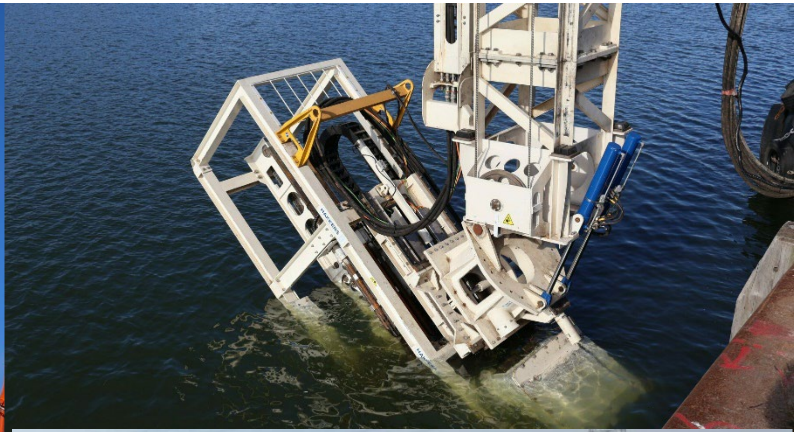
- Optimise carbon footprint for new quay walls

First under water anchors in Rotterdam

Key principle



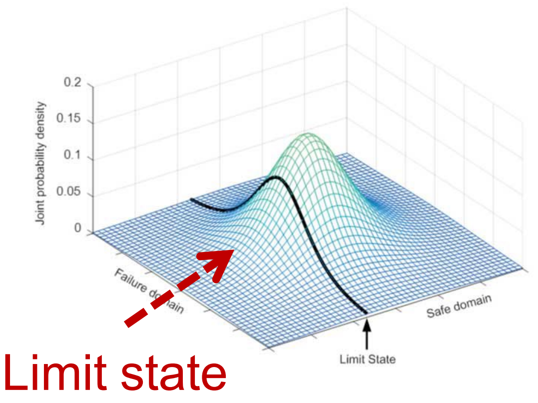


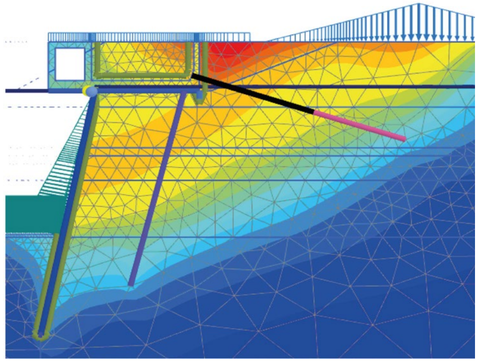


Smet Group HIGH5 SOLUTIONS HAKKERS MAAKT HET MOGELIJK Port of Rotterdam

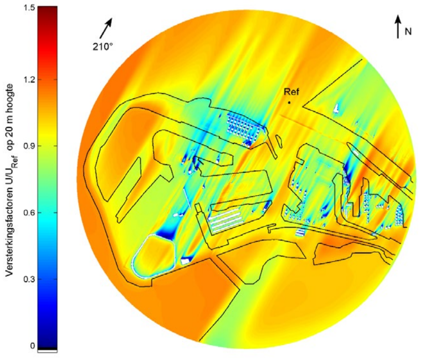
Main trends in quay-wall engineering

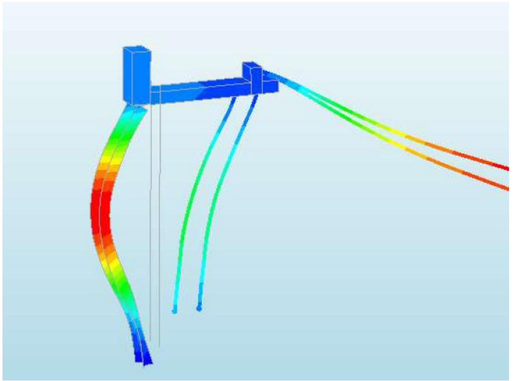
1) Reliability-based assessments



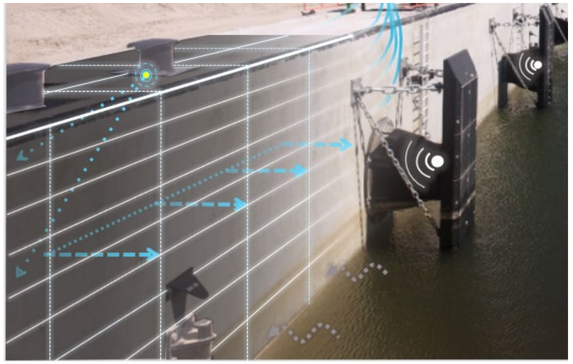


2) Advanced modelling & new methods



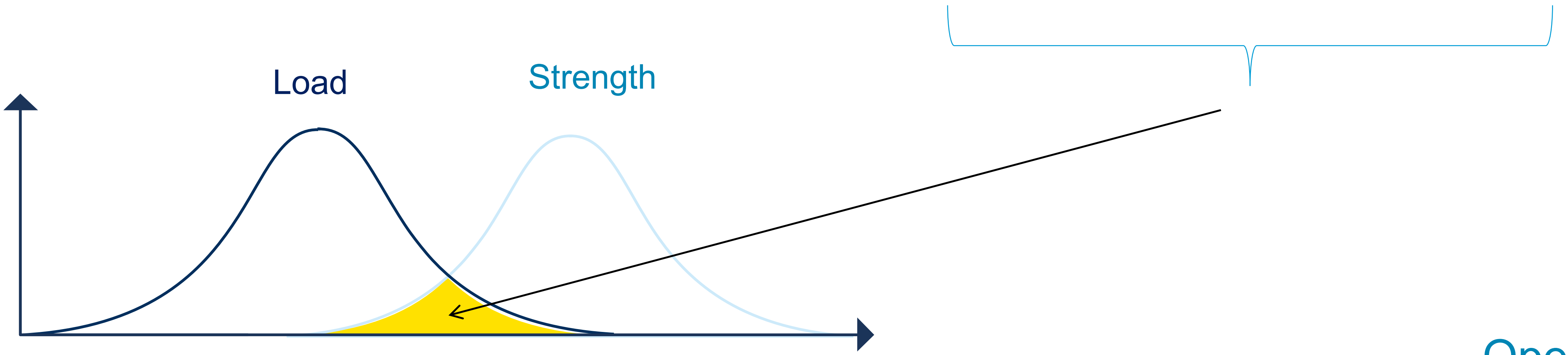


3) Sensoring & digitisation

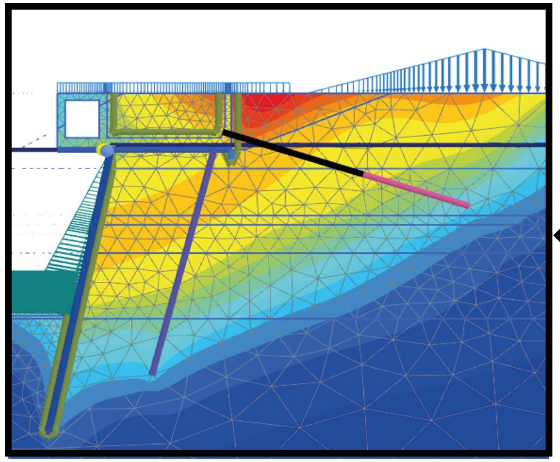


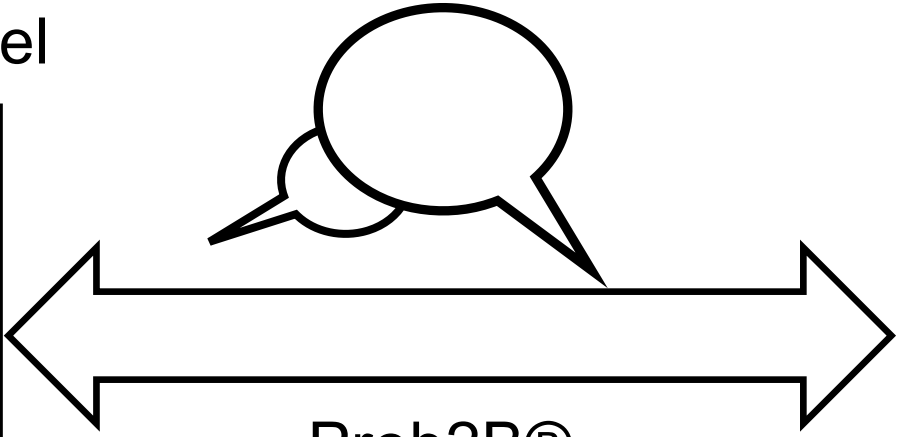
4) Full scale field tests / stress testing

1) Reliability-based assessment: Probability of failure?



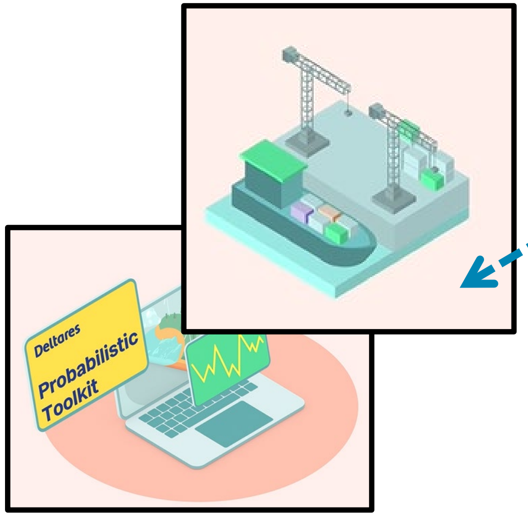
Finite element model





- Prob2B®
- Probana ®
- Deltares Toolkit

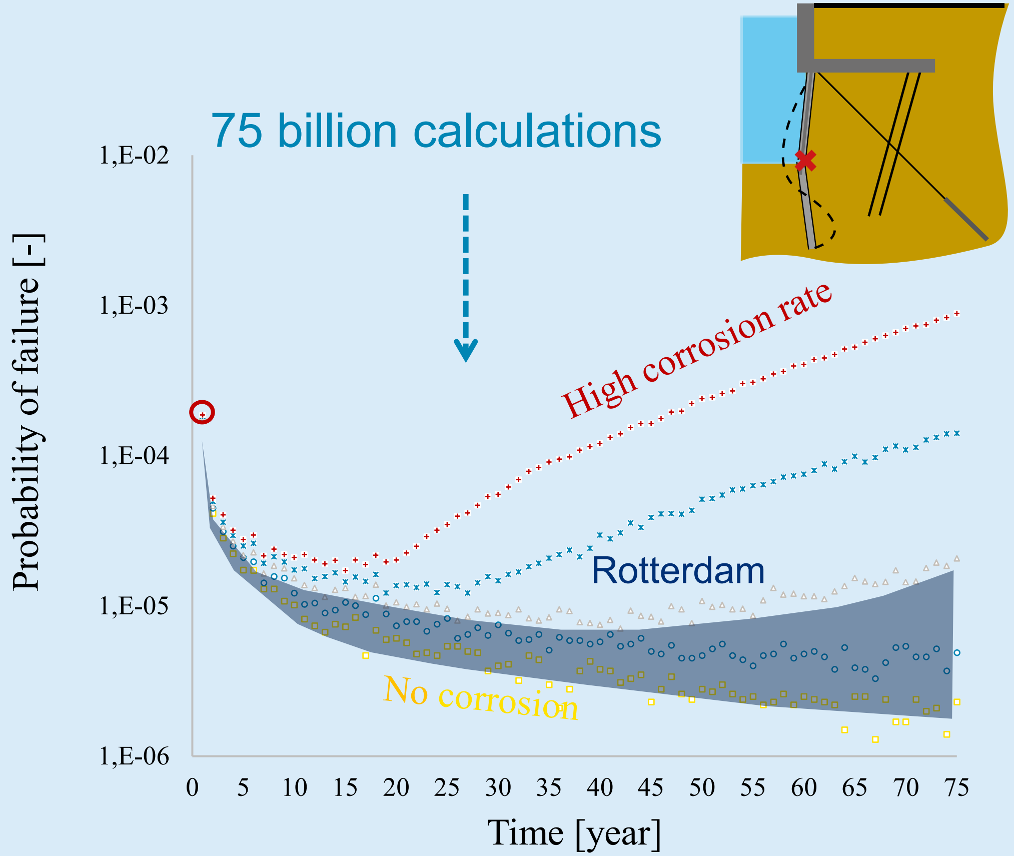
Probabilistic toolbox



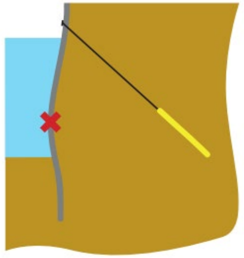
Open-source library with statistical methods

1) Reliability updating & past service performance

- New reliability classes in national annex Eurocode (CC1, CC2 and CC3) for maritime structures.
- Lifetime existing quay walls 35% longer compared to prediction (KMS degradation model PoR). Approx. 25 years extra service life



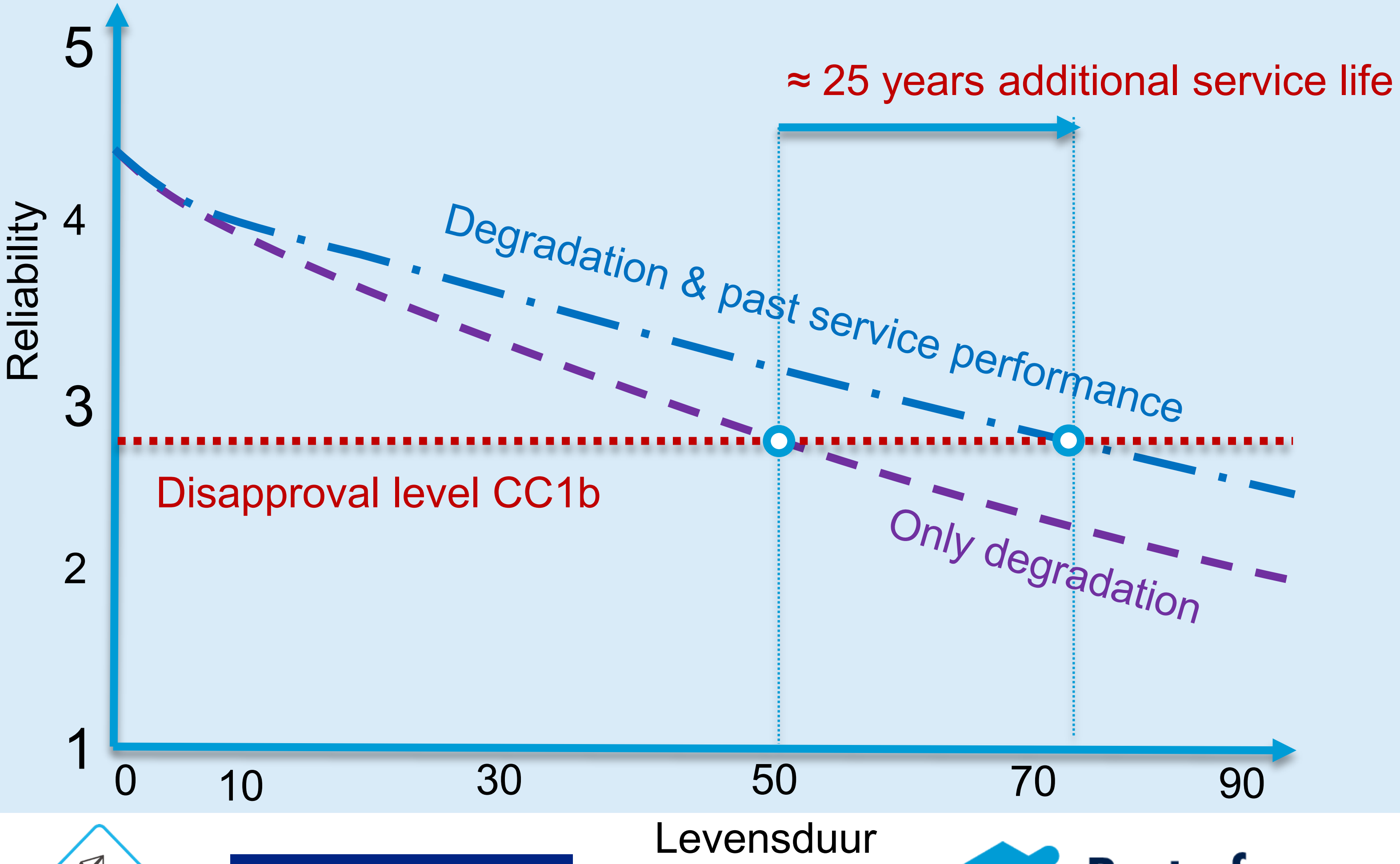
1) NEN Code “past service performance” (2023-2025)



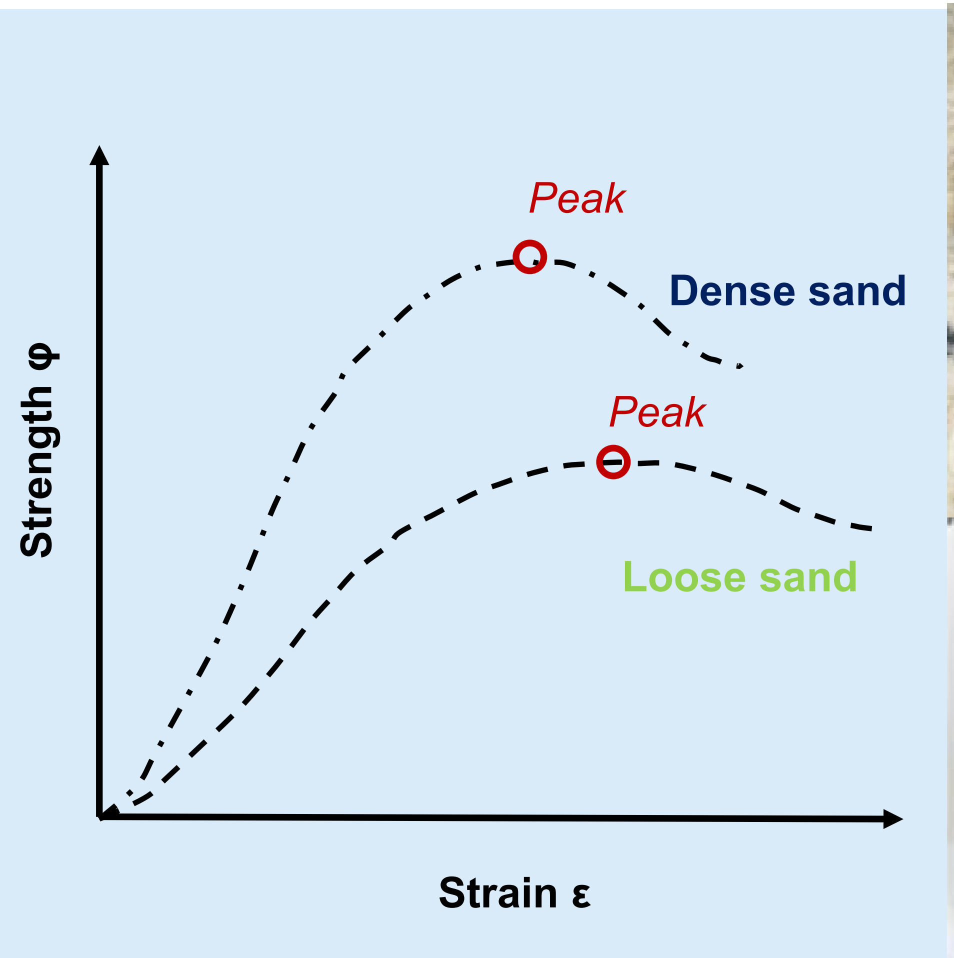
Sheet pile calculation CUR 166:

- Example used to determine safety factors for new sheet pile walls conform CUR 166.
- Despite corrosion lifetime extension of about 10 to 40 years. In this example lifetime extension of about 25 years.
- Annual reliability targets

Gevolgklasse	Jaarlijkse betrouwbaarheidsindex		
	Afkeur	Verbouw	Nieuwbouw
CC1a	1,8	3,6	nvt
CC1b	2,8	3,6	4,2 (3,3)
CC2	3,3	4,0	4,7 (3,8)
CC3	4,0	4,4	5,2 (4,3)

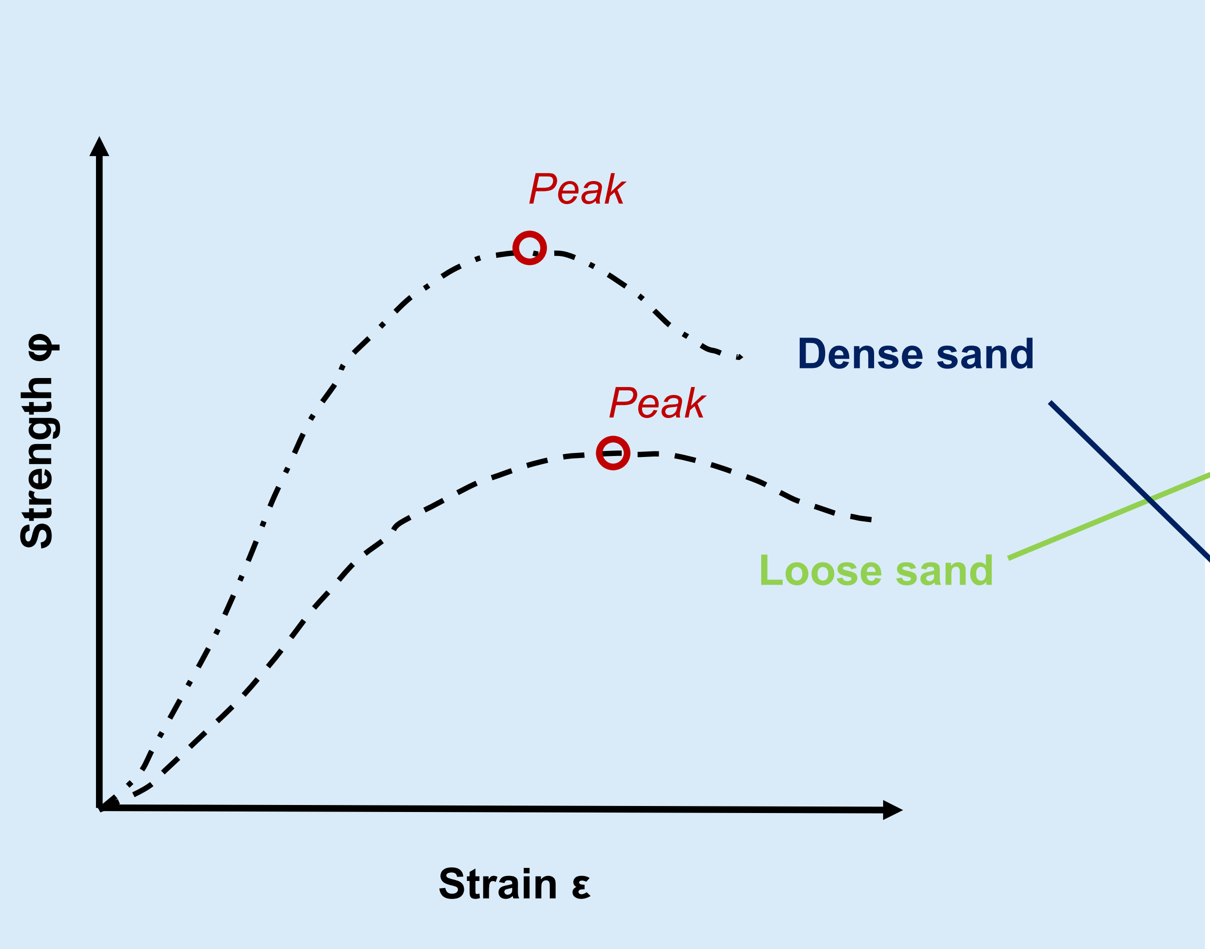


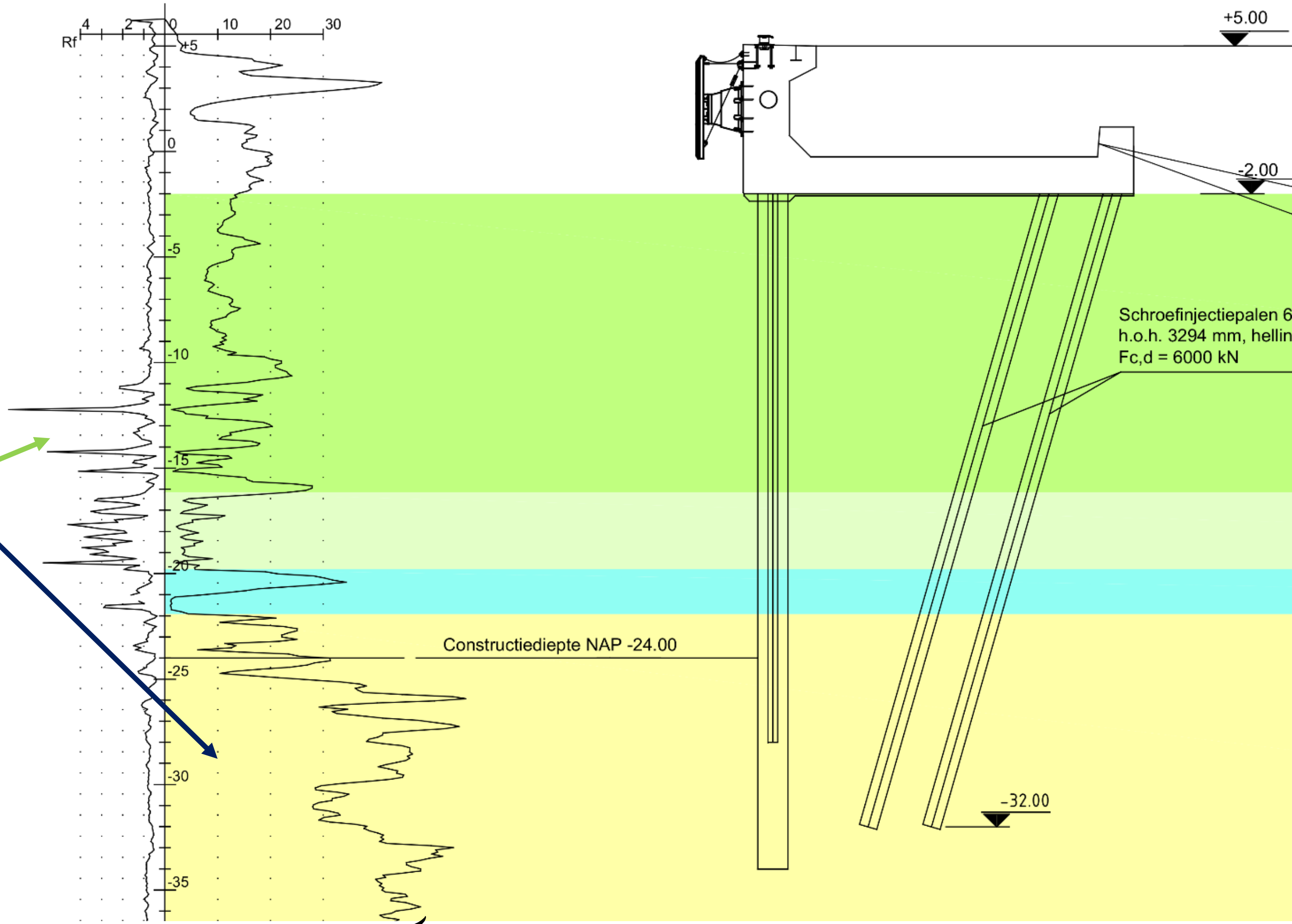
2) Soil strength (plane strain effects)



Triaxial test

2) Soil strength (plane strain effects)





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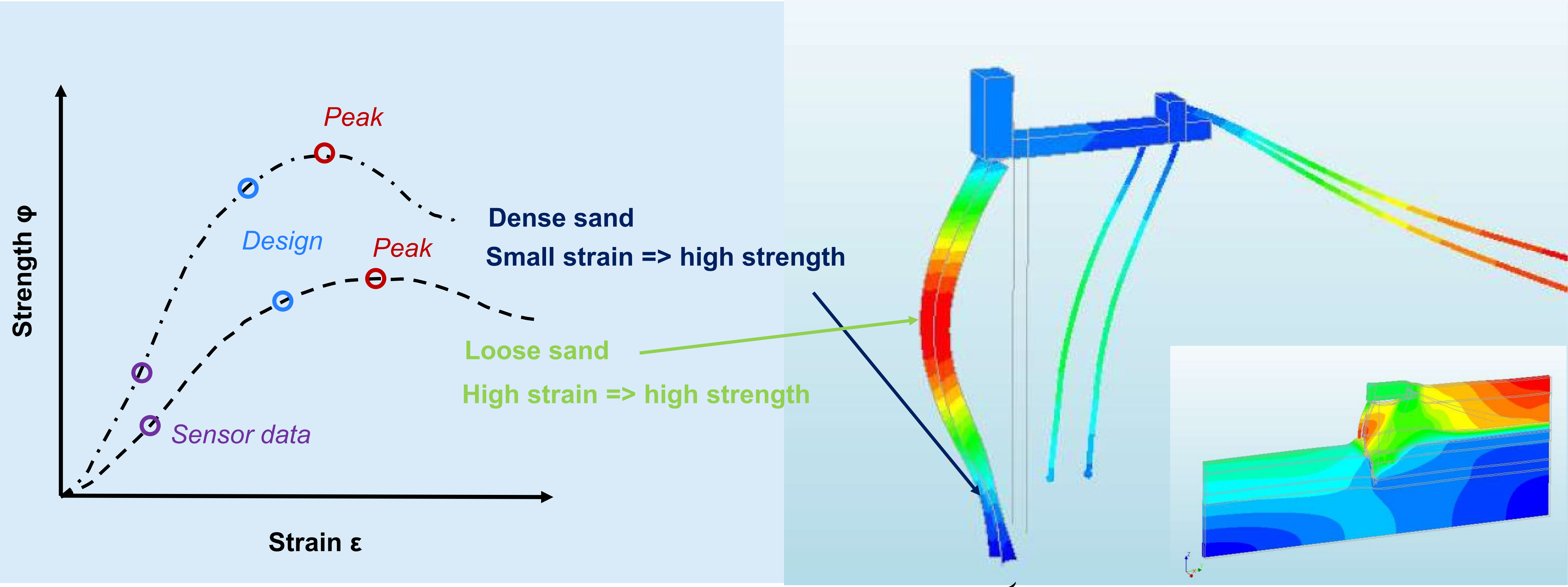
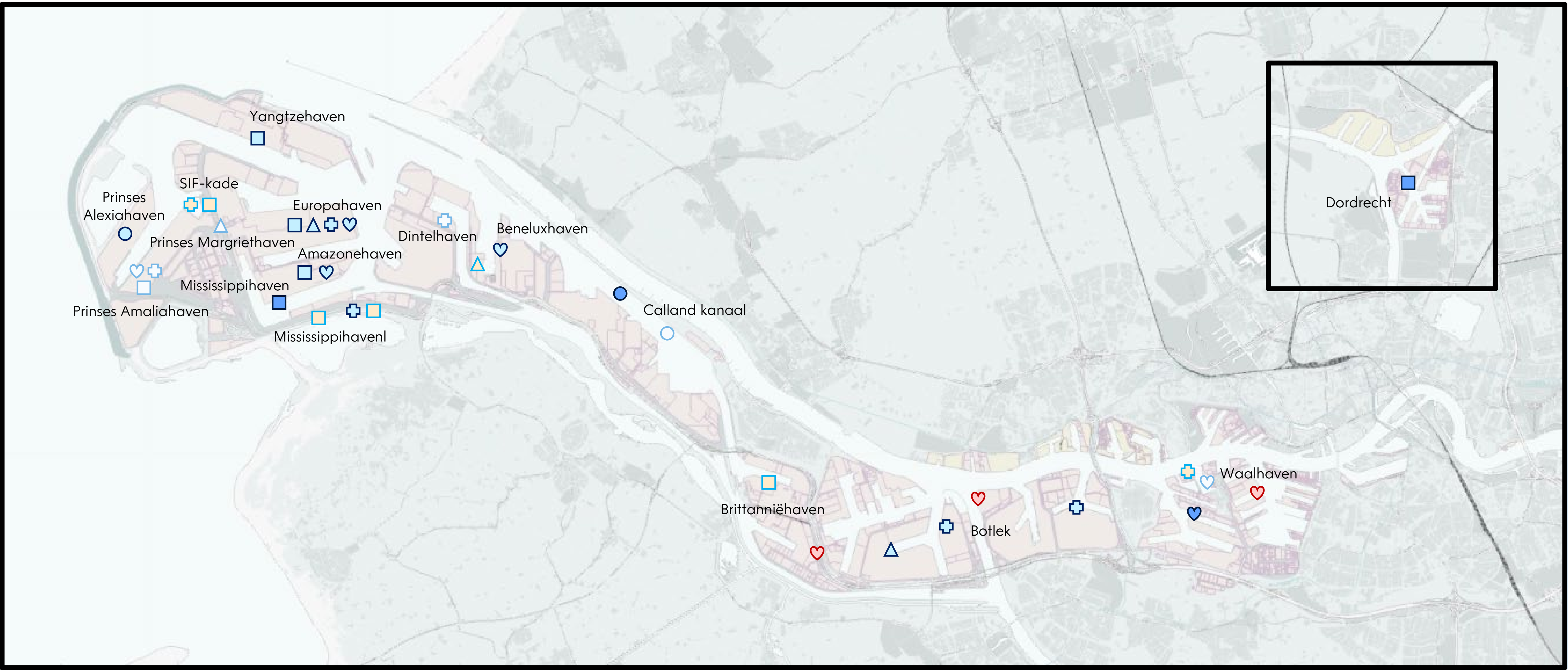


3) Sensoring & digitization



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3) Smart quay walls

- 10 quay walls equipped with sensors.
- Input for advanced modelling or reliability-based assessments.
- Digital twin => Inspector of the future is a sensor!

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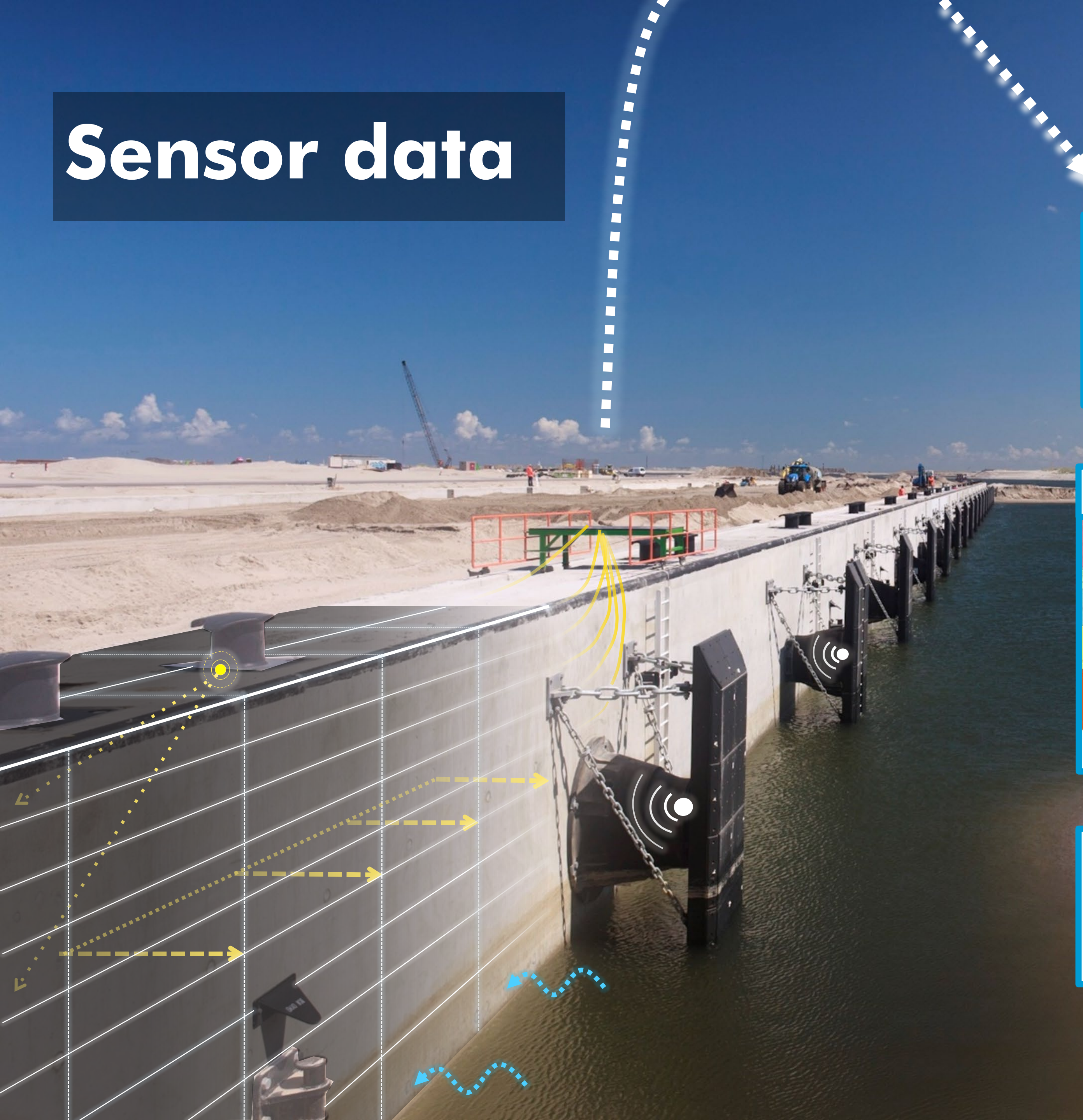
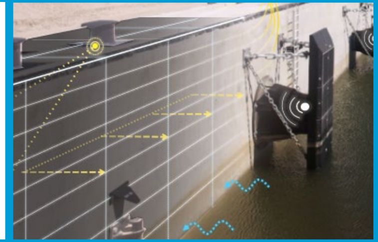
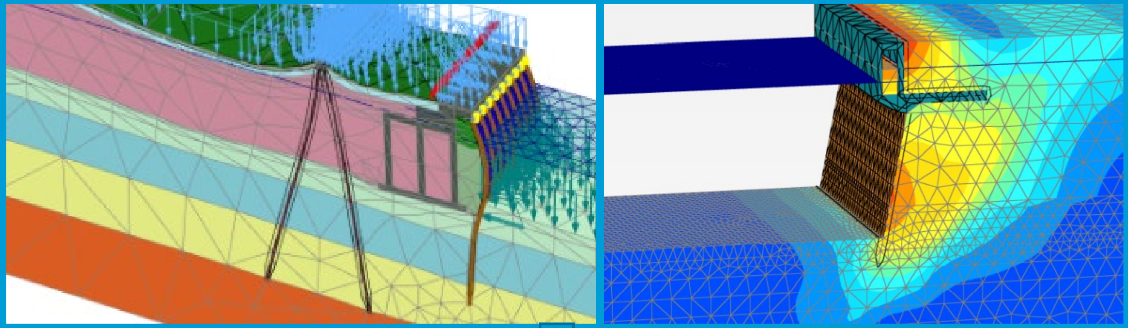
Sensor data



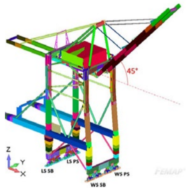
INPUT REVERSE ENGINEERING:
- As-built data
- Smart quay walls (sensordata)
- Construction data, anchor- & pile tests
- New knowledge (e.g. I² & SmartPort)



NUMERICAL MODEL quay wall (2D of 3D)



POSSIBLE OUTPUT:
- Bigger crane.
- Higher loads.
- Additional nautical depth.



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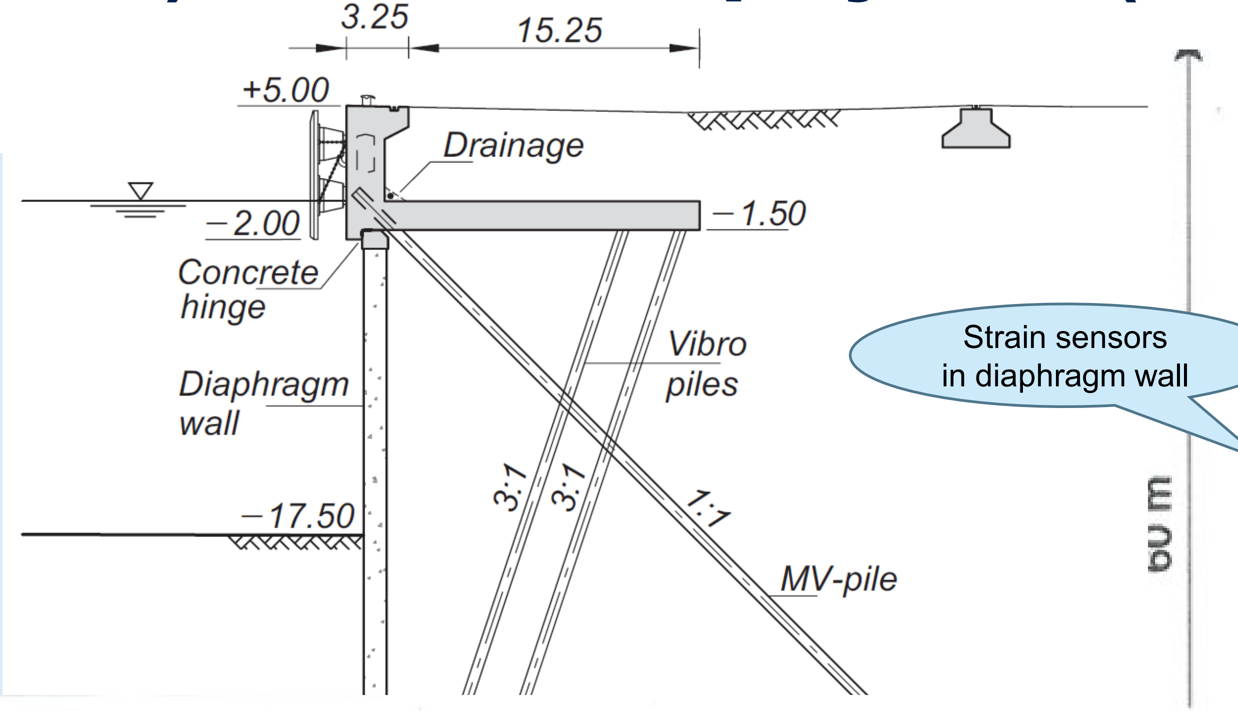
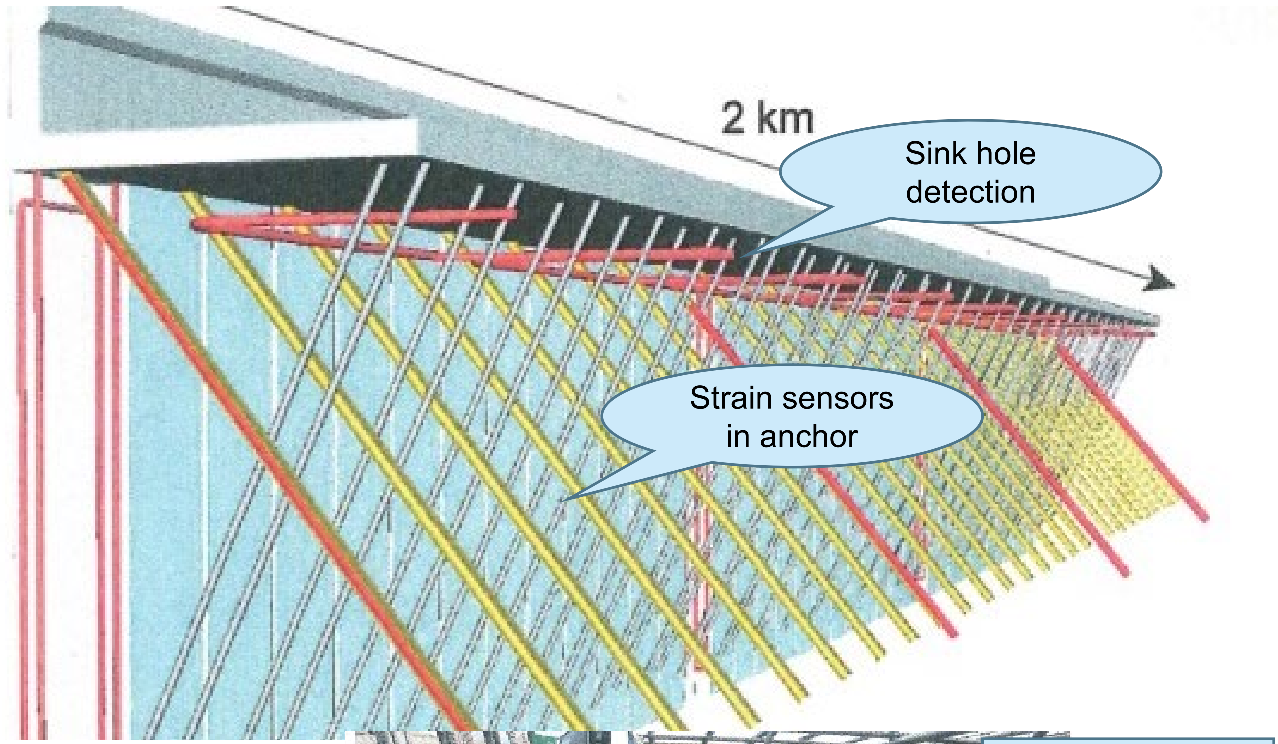
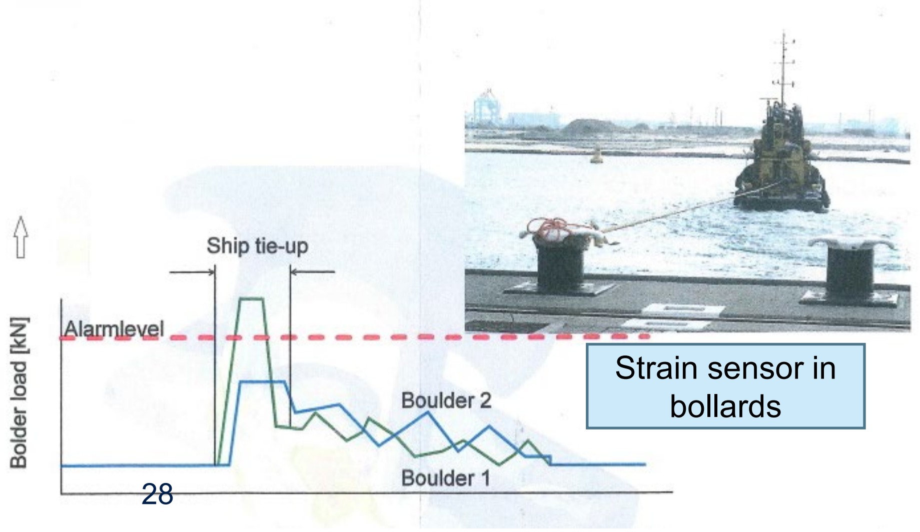
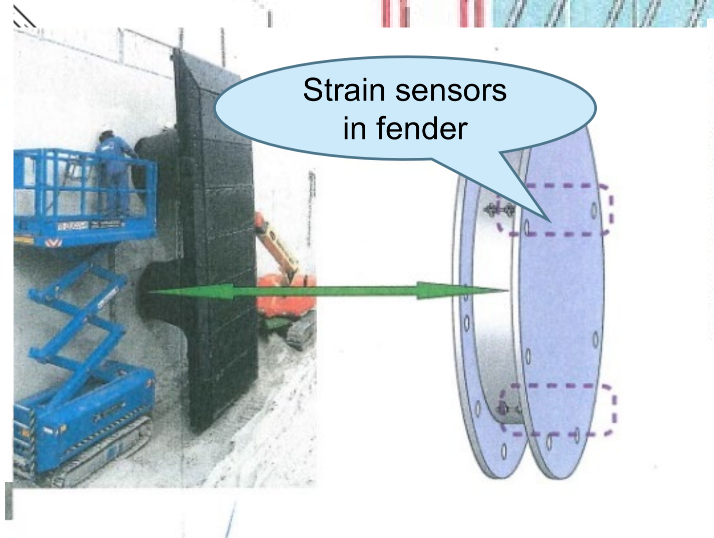
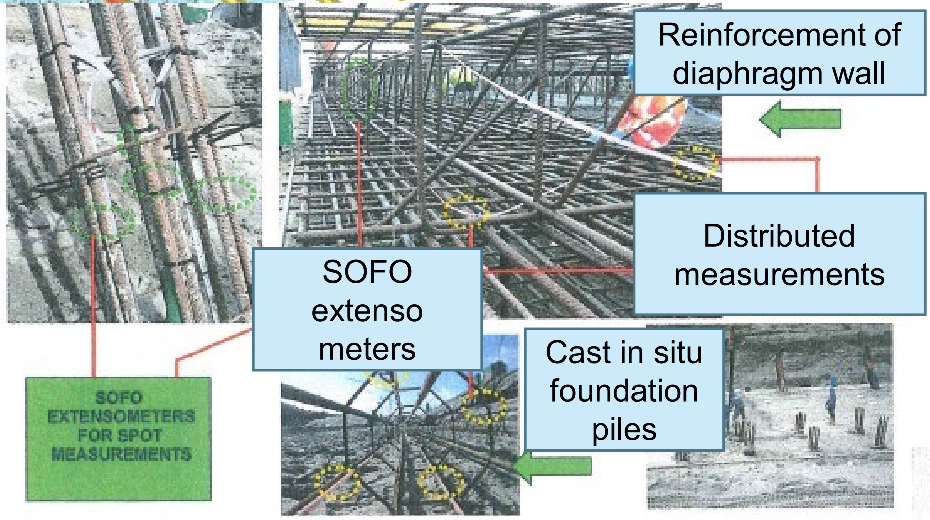
3) First smart quay wall (2008)



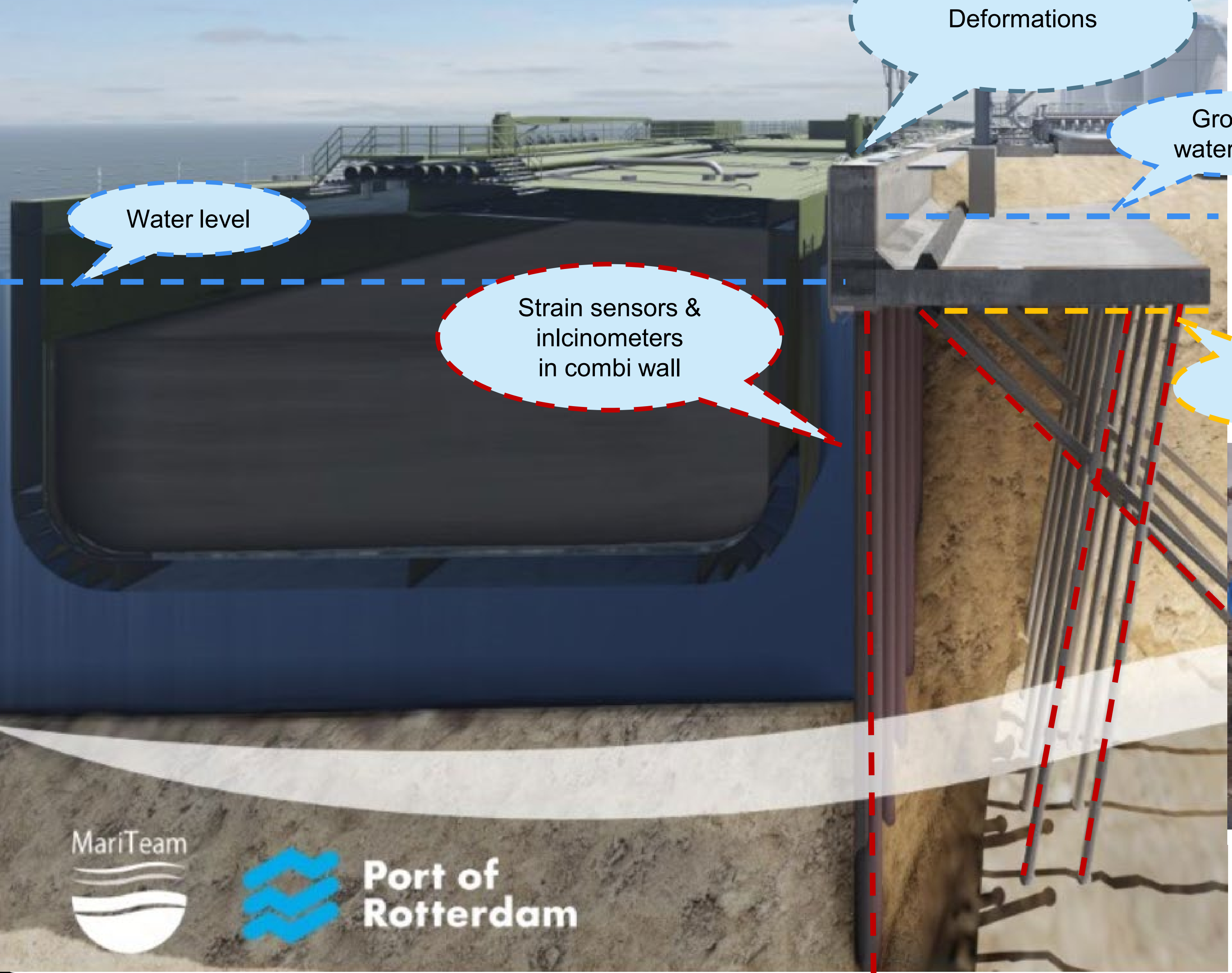


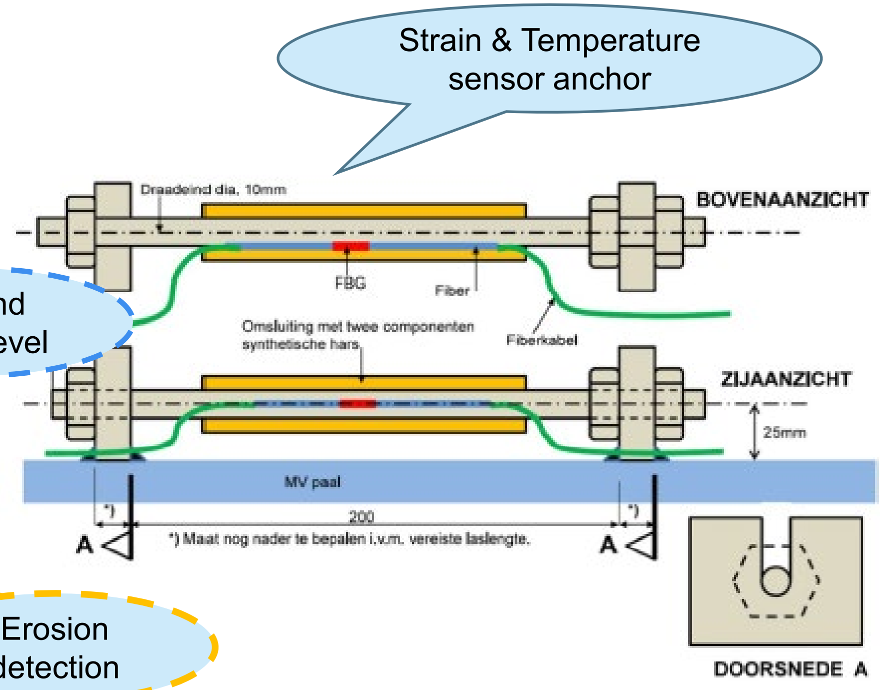


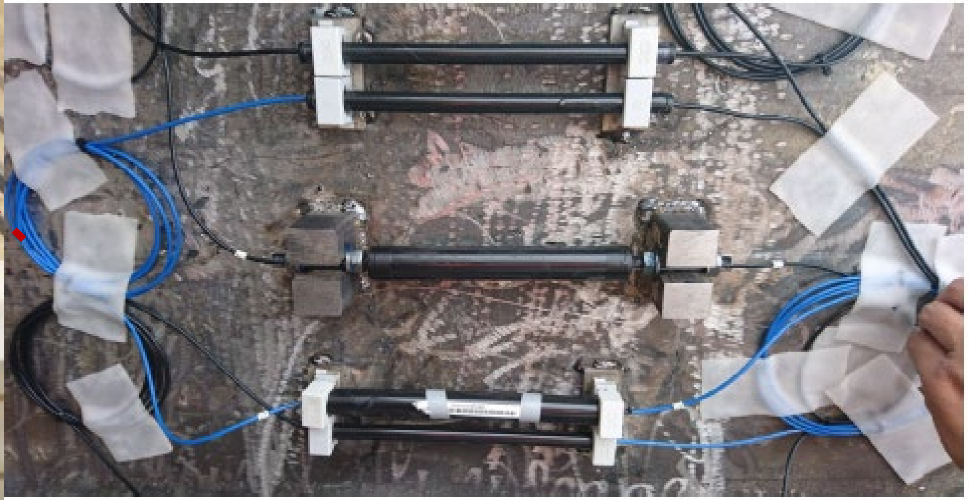




Smart quay wall Maasvlakte





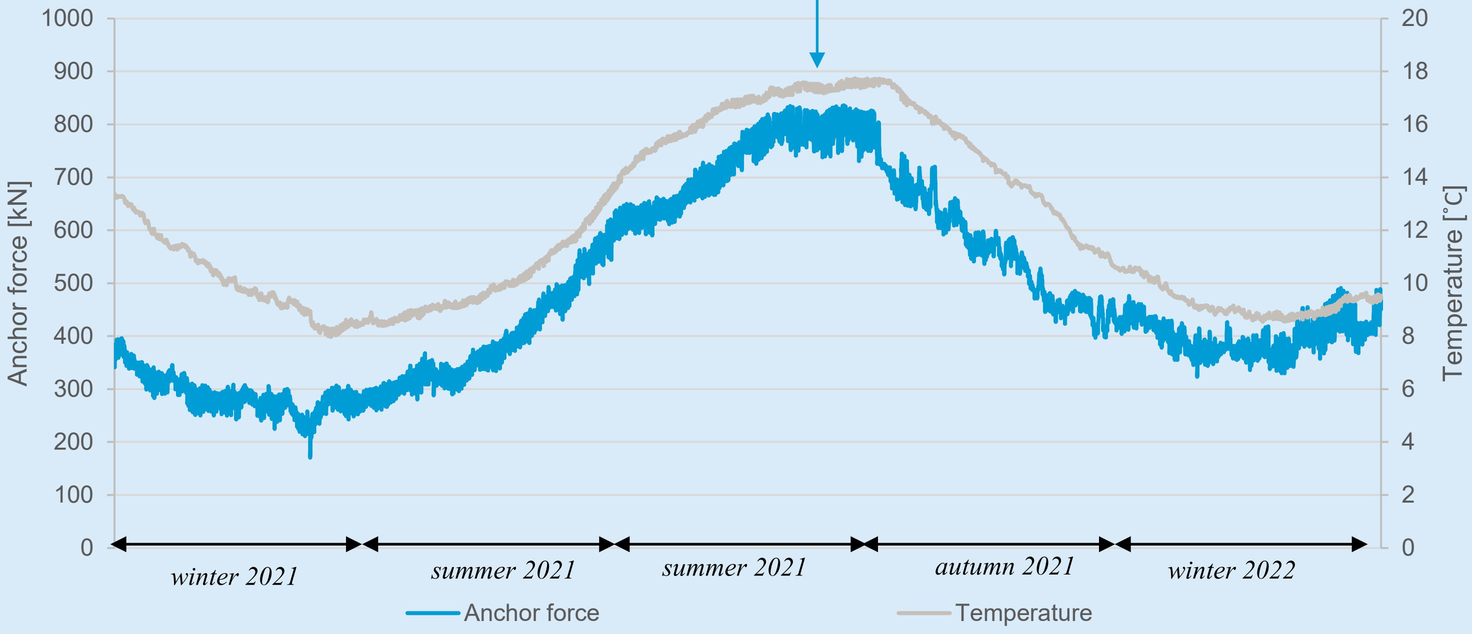


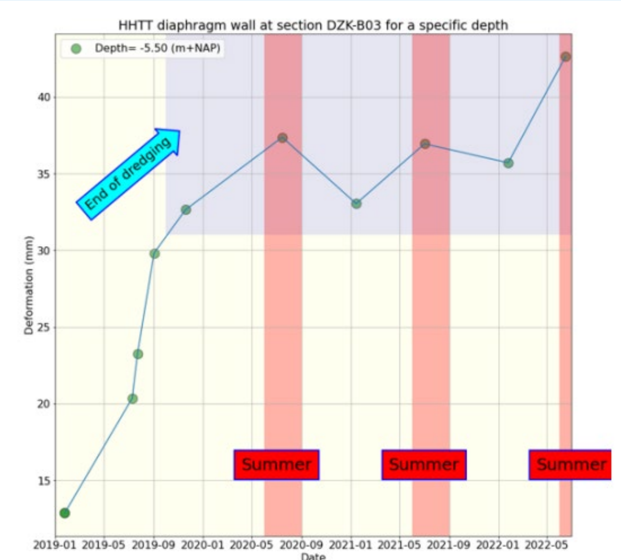
3) Smart quay walls: Anchor Force

- Lower compared to design value.
- Reduce model uncertainty.
- Input for checking the influence of climate change on quay-wall behaviour.

Design value is 2000kN

Hidden safety?

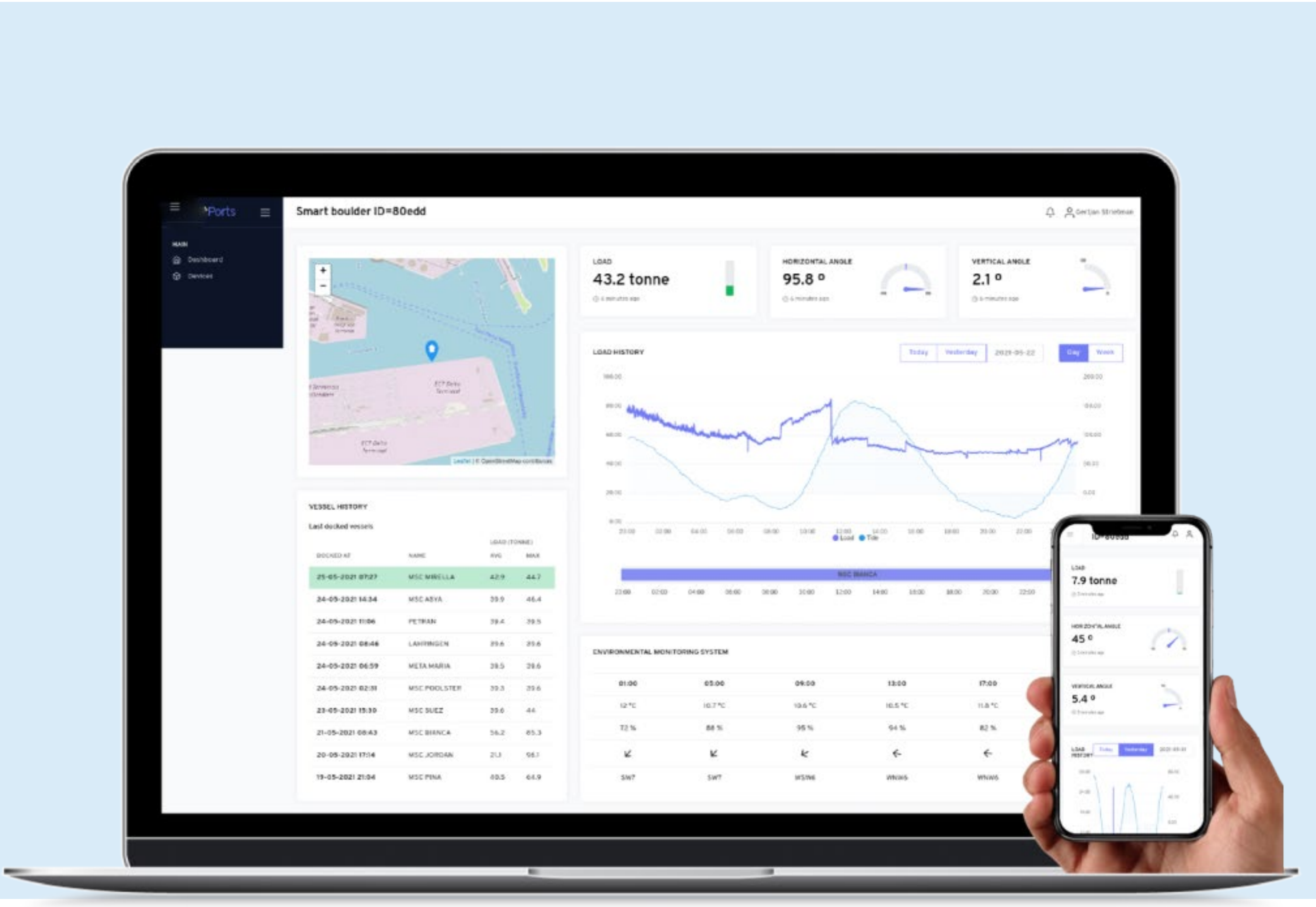


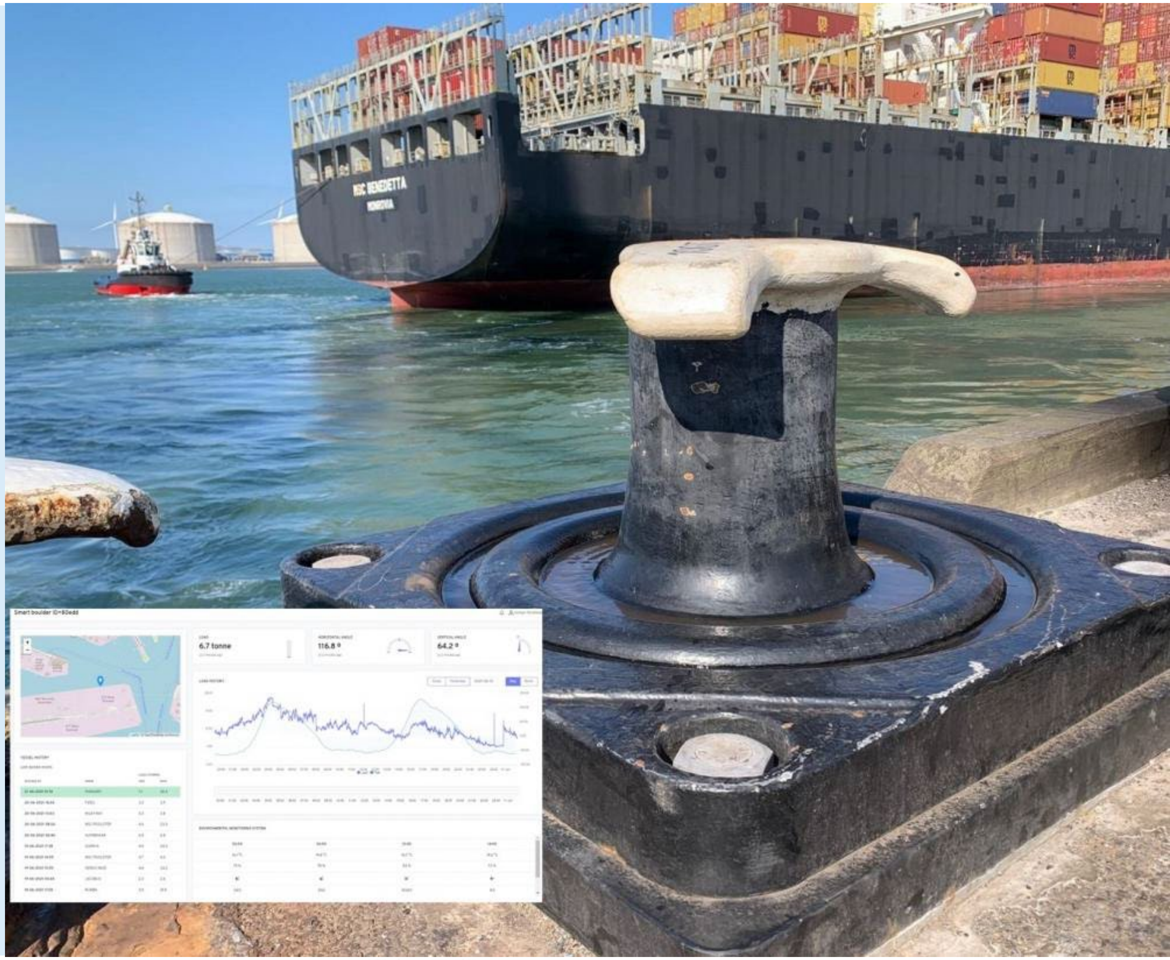


TU Delft

Port of Rotterdam

3) Data analytics: Example Smart Bollard



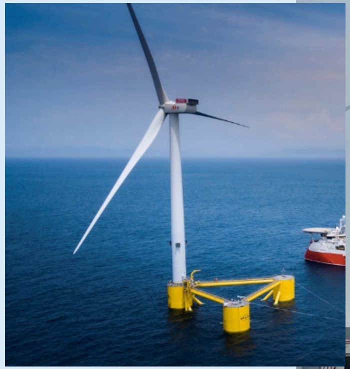


STRAATMAN BV
Mooring & Dredging Equipment
Port of Rotterdam

4) Full scale field test open ended steel tubes

Scope:

- 4 test piles ø1220 (D/t of 60, 80 and 100).
- Spider-shaped test frame for static test
- Tension frame for cyclic test.
- Advanced strain and pressure sensors.
- Max test load 25.000 kN/ 15.000 MN.
- Costs about €2.5m.



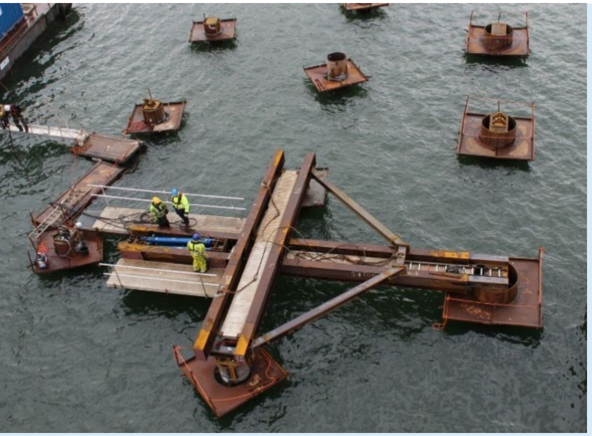
⇒ 5% less material for combi tubes (1-2m shorter)

⇒ > €100m and 100 kton CO_2 savings per off shore wind farm

bluewater TU Delft wtcb.be Witteveen+Bos DIMCO Infra Marine Contractors Port of Rotterdam

4) Full scale field tests & stress testing

Flexible dolphin (2014)



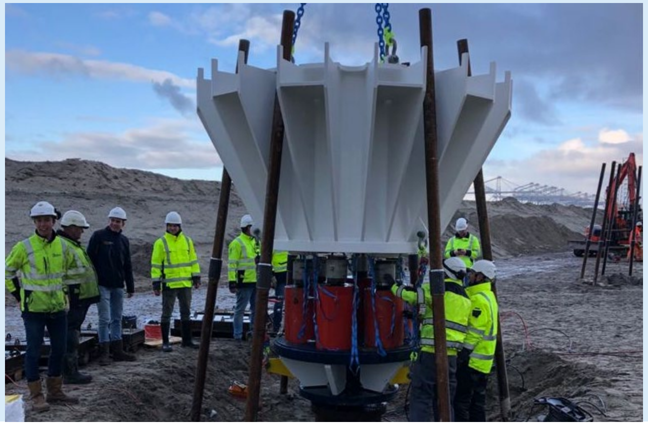
Precast concrete piles (2017;'21)

Sheet pile piles (2018)

Urban quay wall (2022)

Anchors (2017;'18,'19,21,'22)

Cast in situ piles (2020)



Bow-thruster loads (2019;'21)

Full-scale test quay wall

Port of Rotterdam

(2024/2025)

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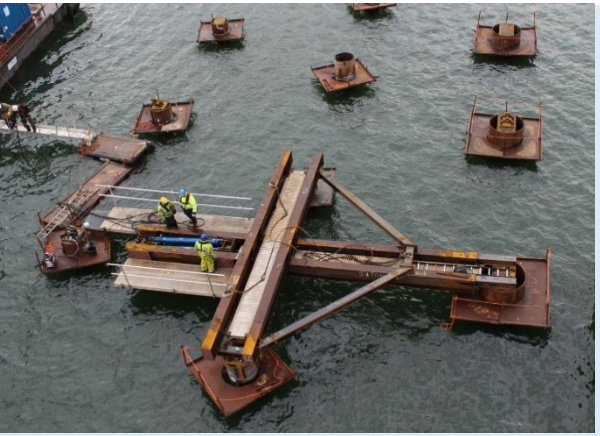
4) Full scale field tests & stress testing

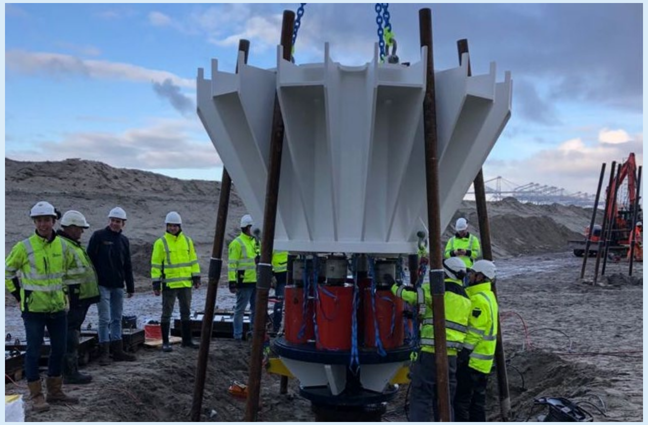
A) Flexible dolphins



B) Precast concrete piles

C) MV-pile anchors

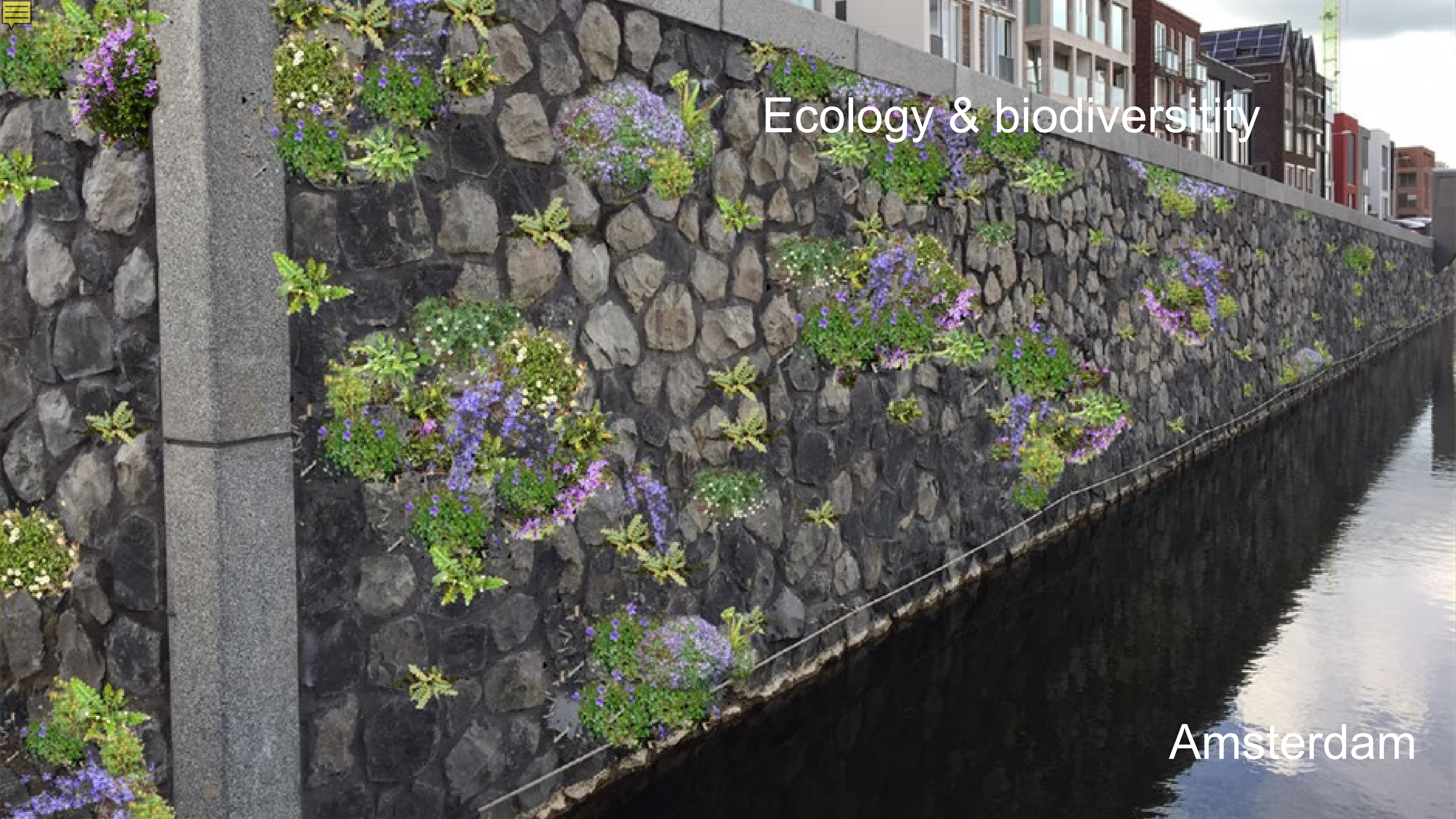
D) Precast concrete, cast in situ & SI piles



Project	n	Costs	Direct savings		Annual future savings[a]	
	[-]	[m€]	[m€]	[kton CO_2]	[m€]	[kton CO_2]
A) Dolphins 2014	8	0.75	6.10	0.25	6.00	0.30
B) Precast concrete 2017	4	0.45	0.55	0.75	n/a	n/a
C) Anchors 2017-2022	6	0.75	4.50	1.00	3.00	1.50
D) Cast in situ 2020	11	2.50	15.50	11.00	12.50	10.00
Total	29	4.45	26.65	13.00	21.50	11.80

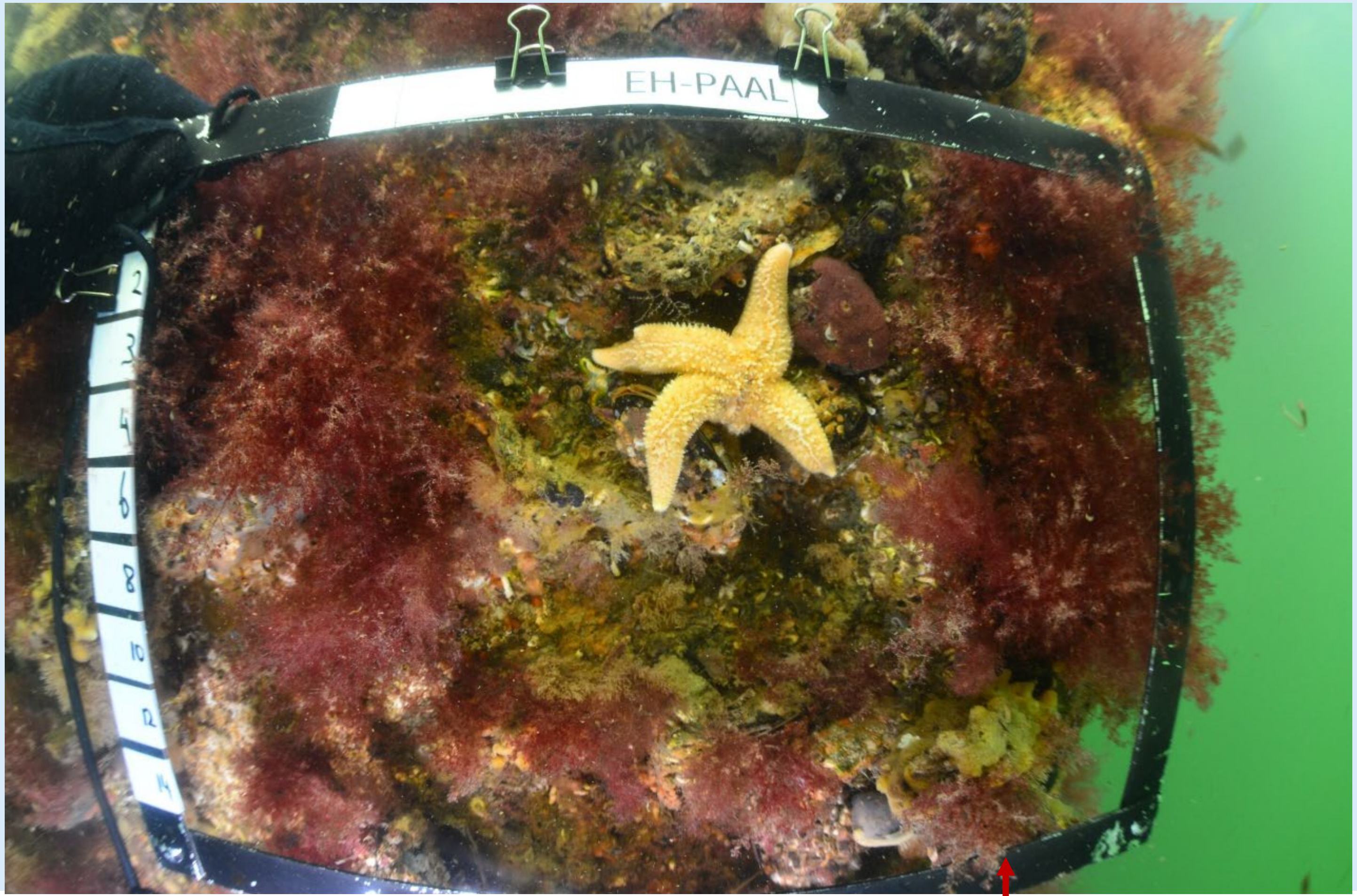
FULL-SCALE TEST QUAY WALL MAASVALKTE

Port of Rotterdam


Ecology & biodiversitity
Amsterdam

NATURE INLCUSIVE DESIGN

Beneluxhaven



Europahaven

Port of Rotterdam

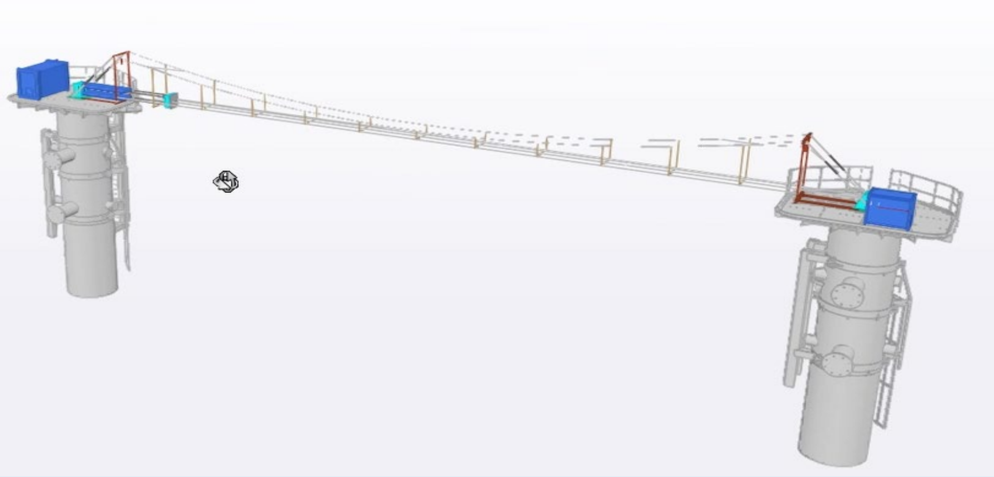
REMOTE SETTING PLATTE OESTER (RESO)

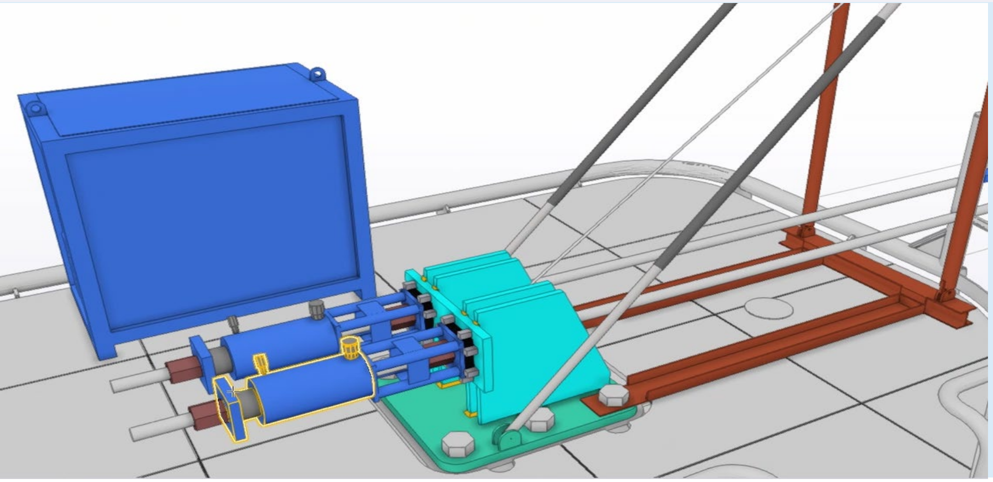
Steen met oesters

Monitoren ontwikkeling

Thank you for your attention.

Full-scale field test Calandkanaal 2022





deKlerk WERKENDAM

deBoer Civiele technieken deBoer bv

Witteveen + Bos

Ingenieurs met passie voor techn

Gemeente Rotterdam

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Full-scale field test Calandkanaal 2022

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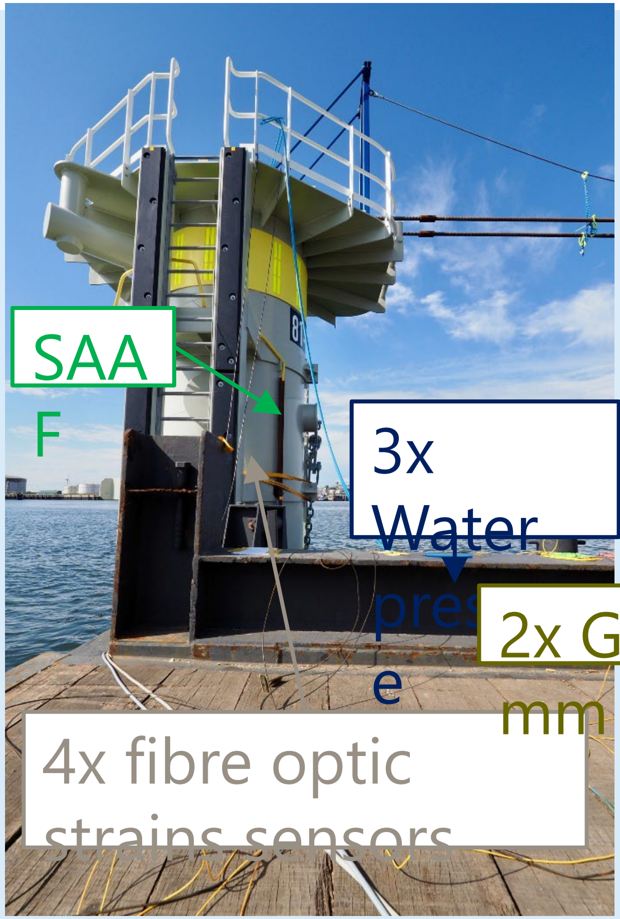
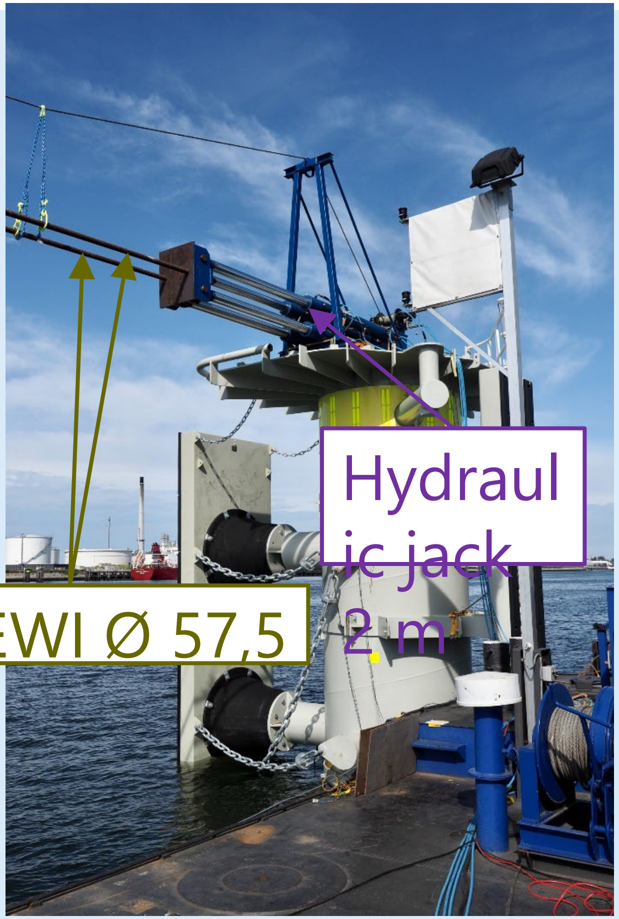
Full-scale field test Calandkanaal 2022

Scope

- Two open ended steel tubes.
- Tube diameter 2.4m.
- Pile length 48m.
- Test load ≈ 1820kN (90% of ULS design load)
- Max deformation ≈ 1m.
- Sensors: BOFDA fibre optics, SAAF, water pressure sensors, total station.





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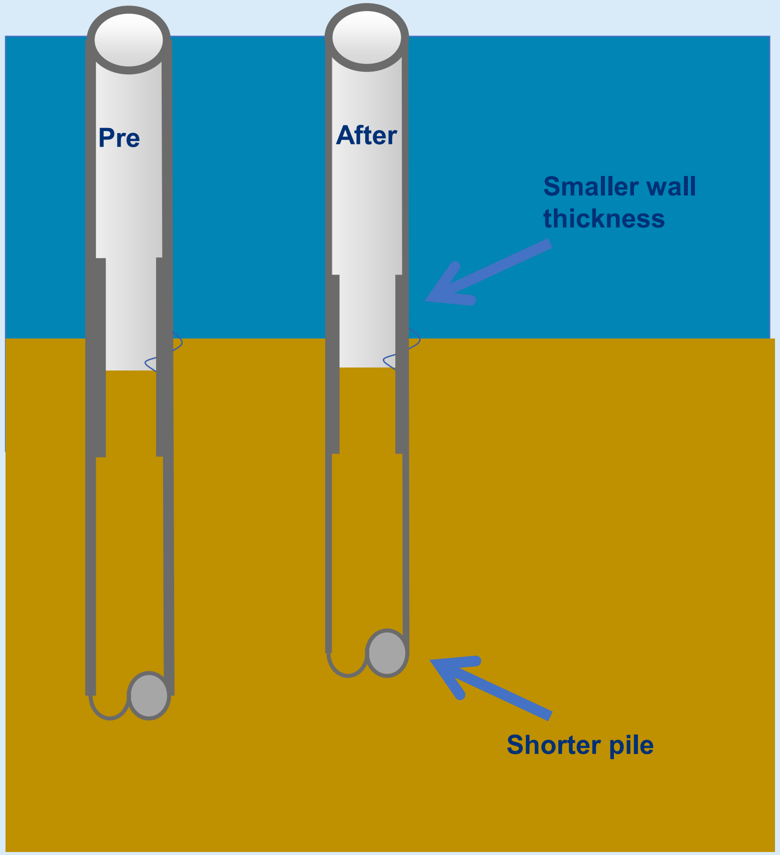
Full-scale field test Calandkanaal 2022

Results:

- New guidelines for soil fixation for different design methods (e.g. Blum, p-y cures and finite element models such as Plaxis)
- SLS fixity check: 50% mobilisation of passive soil wedge after 2nd berthing impact.
- ULS geotechnical failure 100% mobilisation of passive soil wedge (ULS energy once in the service life)



Value:

- Shorter dolphin piles and smaller wall-thickness.
- ≈ 12.5% material savings => cost reduction of €20k and 30 ton CO_2 per pile!