SMART QUAY WALLS
PORT OF ROTTERDAM

Smart quay walls & trends in quay-wall engineering

Alfred Roubos: Port of Rotterdam Authority & TU Delft

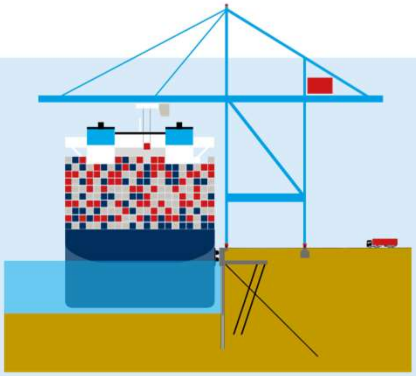
Kivi Symposium:
Data-gedreven Assetmanagement van Kademuren
Delft, The Netherlands

PAO TECHNIEK EN MANAGEMENT | TU Delft | SMART PORT | Port of Rotterdam

Introduction: Alfred Roubos

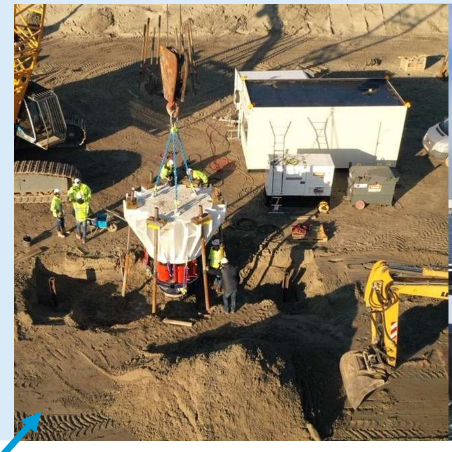
PhD: reliability of quay walls

- Port Engineer (≈ 15 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



Full scale field test foundation piles

Bow-thruster induced scour

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Content

- Introduction
- Trends in quay-wall engineering

1. Reliability-based assessment
2. Advanced modelling
3. Sensoring & digitisation
4. Stress testing / field observations

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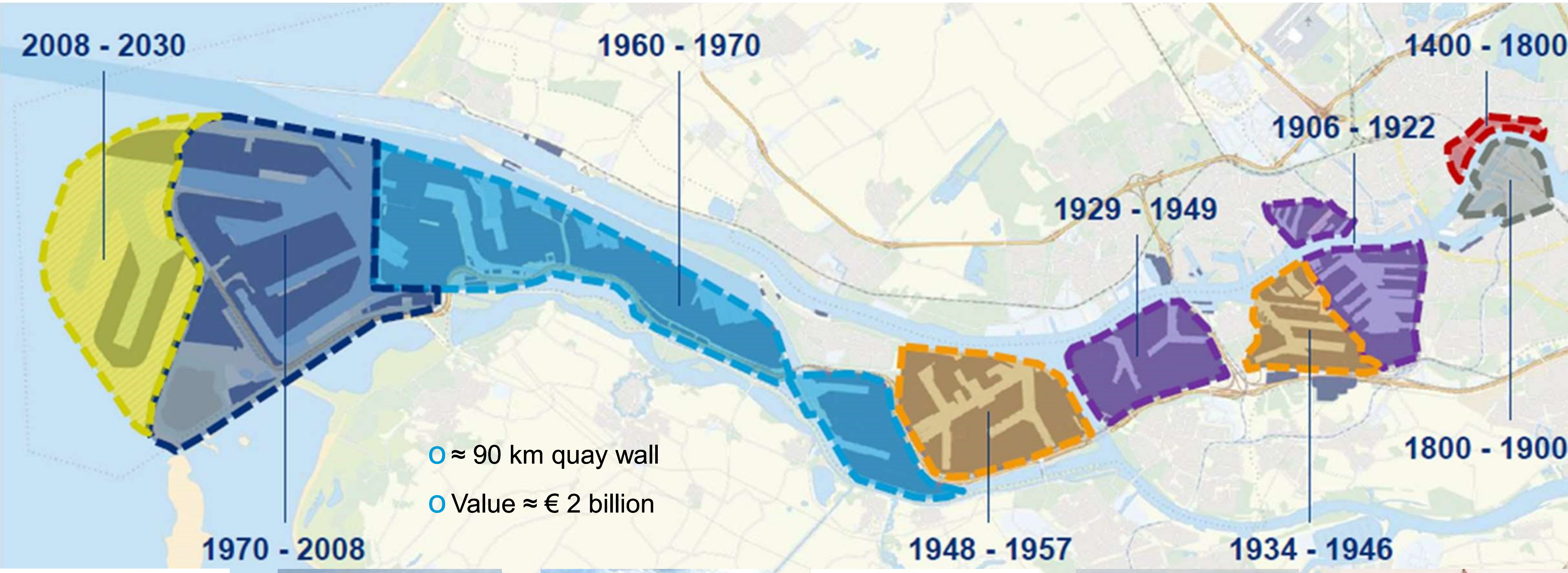
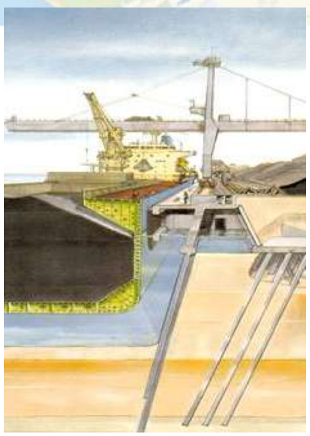
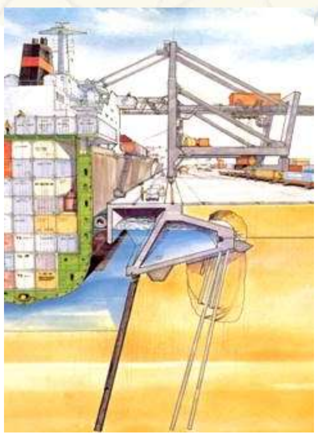

2008 - 2030
1960 - 1970
1400 - 1800
1906 - 1922
1929 - 1949
1800 - 1900
o ≈ 90 km quay wall
o Value ≈ € 2 billion
1970 - 2008
1948 - 1957
1934 - 1946

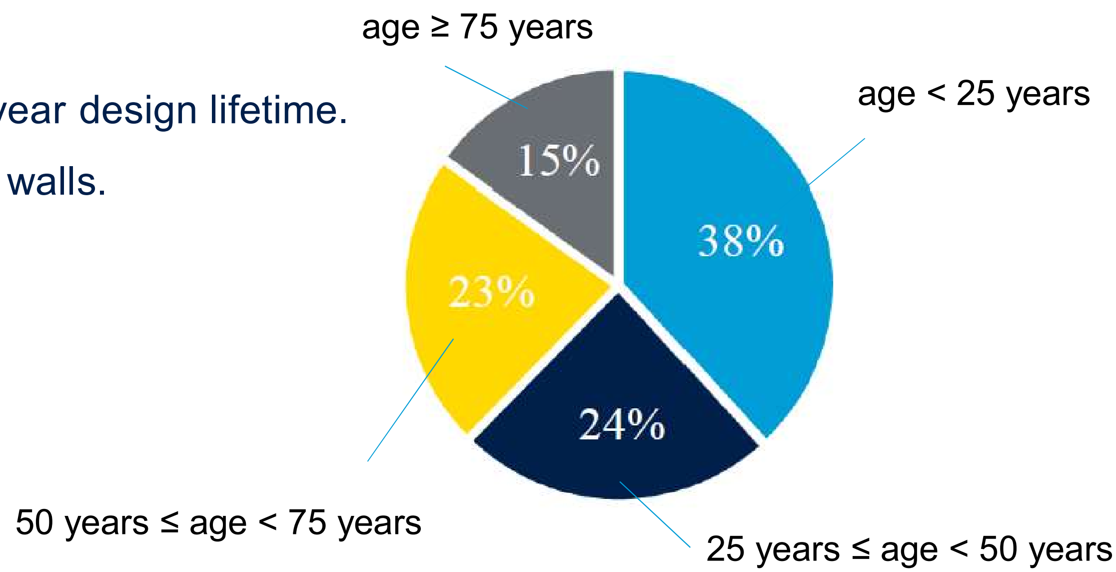


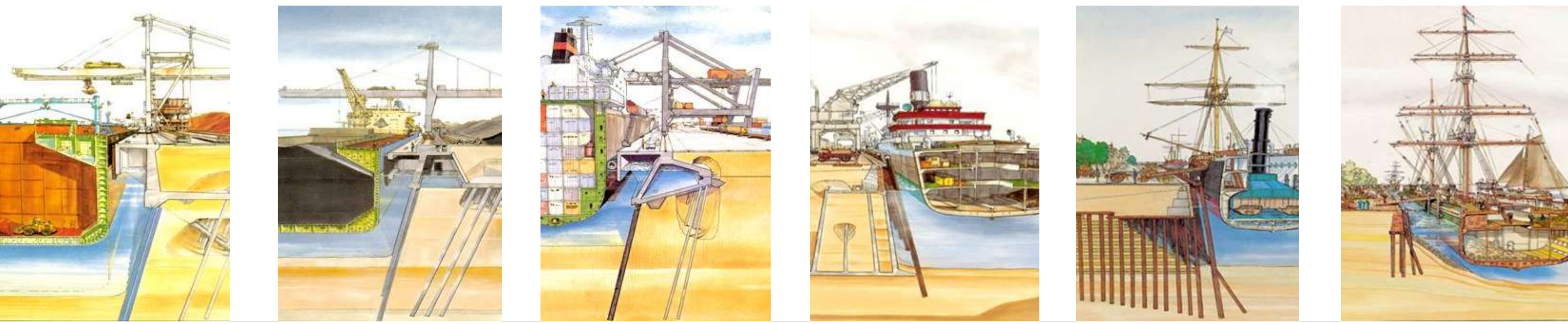


Situation in Rotterdam

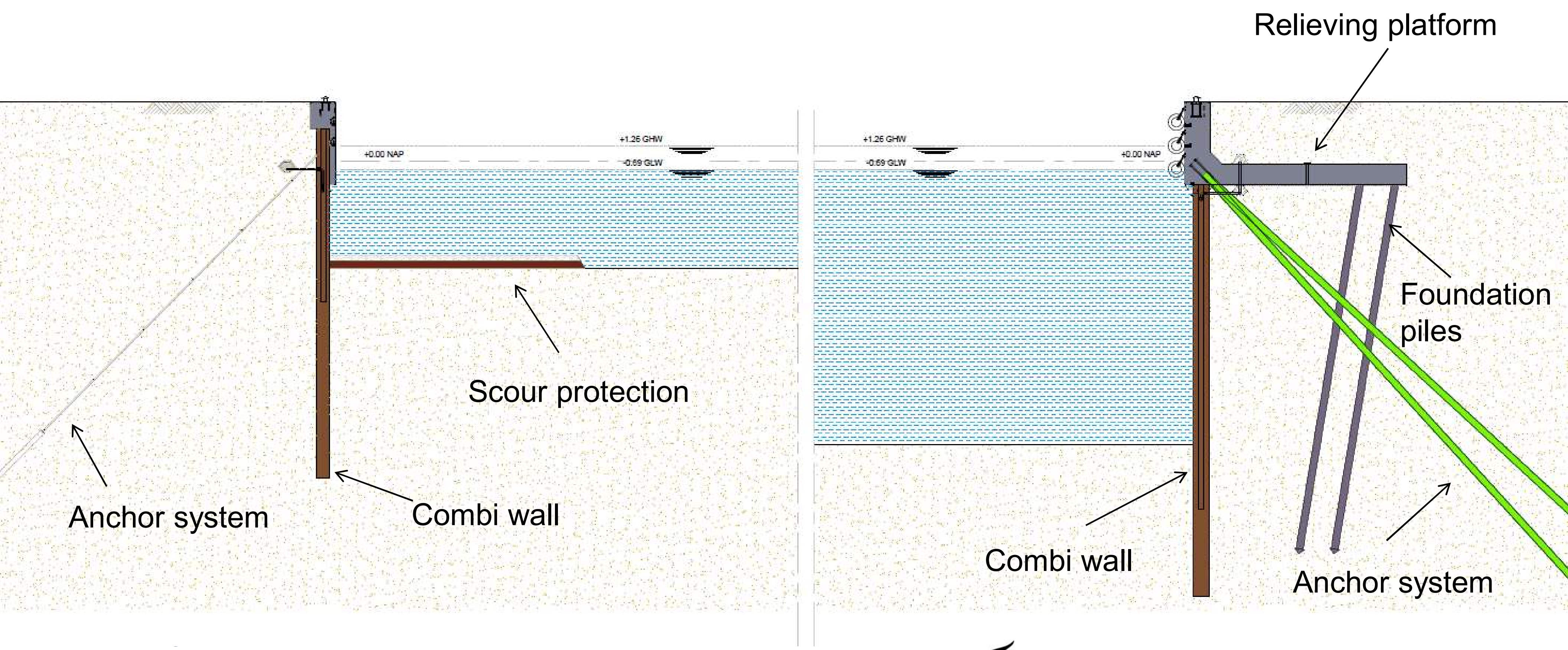
- Many quay walls approach the end of their fifty-year design lifetime.
- Focus will shift towards assessing existing quay walls.
- Most quay walls are in good condition.

⟹ Not yet the end of their service life!





Standard quay-wall design solutions



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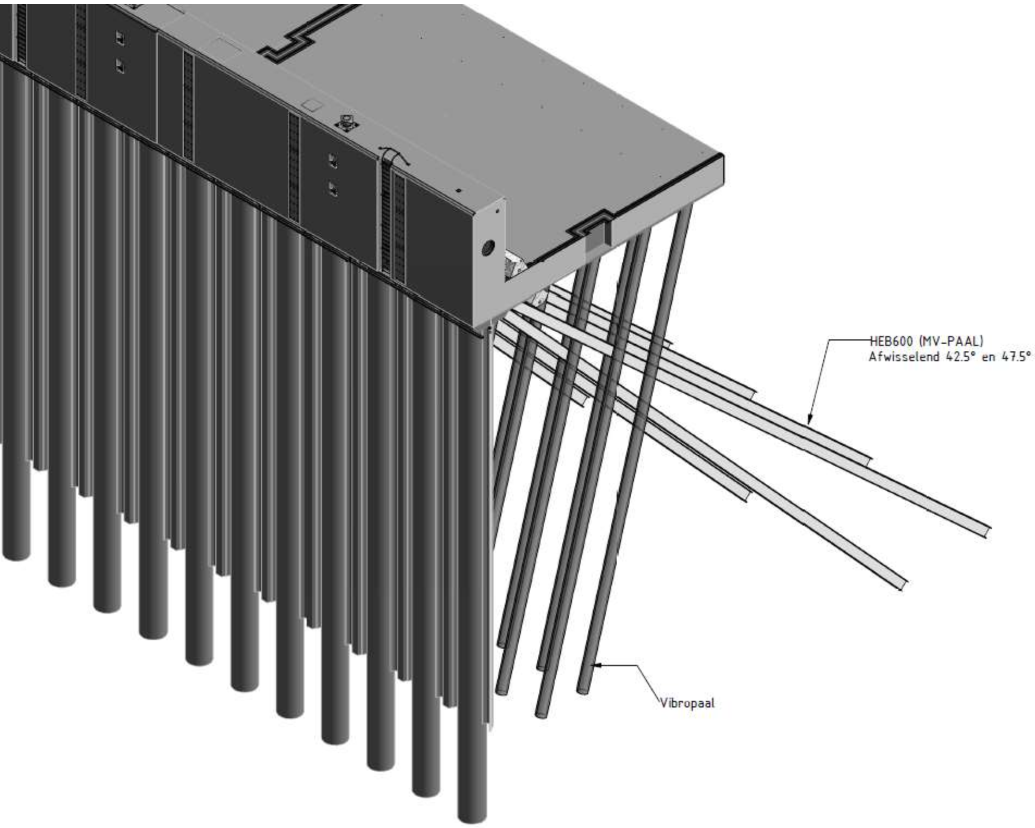
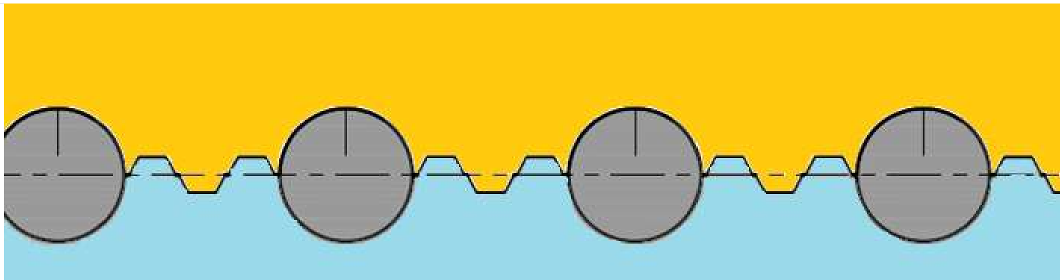
Typical combi wall



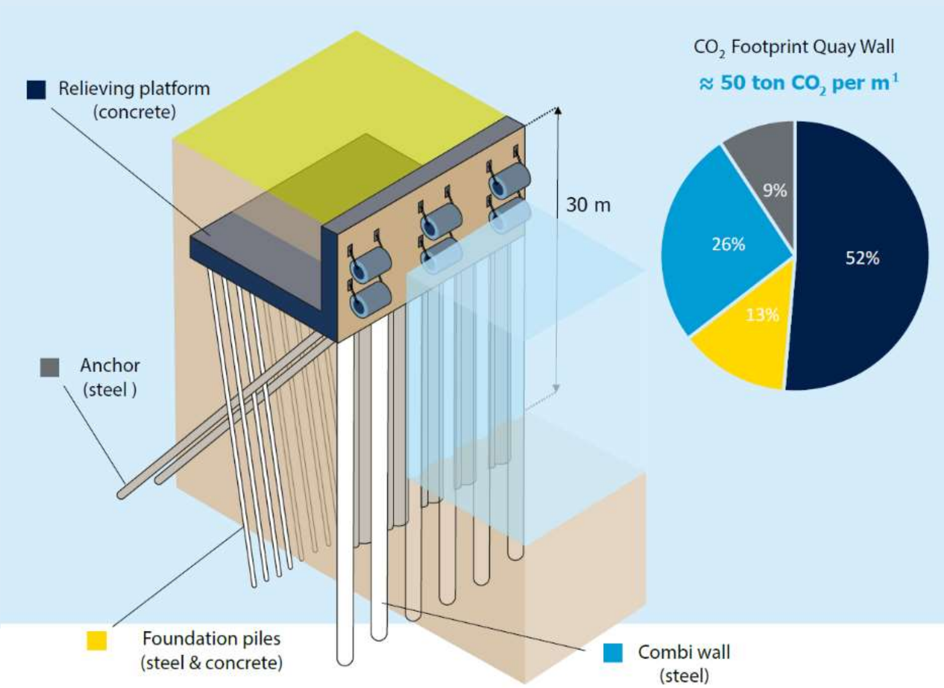


Typical combi wall

Vision & Ambition

Existing structures

- Lifetime extension and optimize/maintain functionality.



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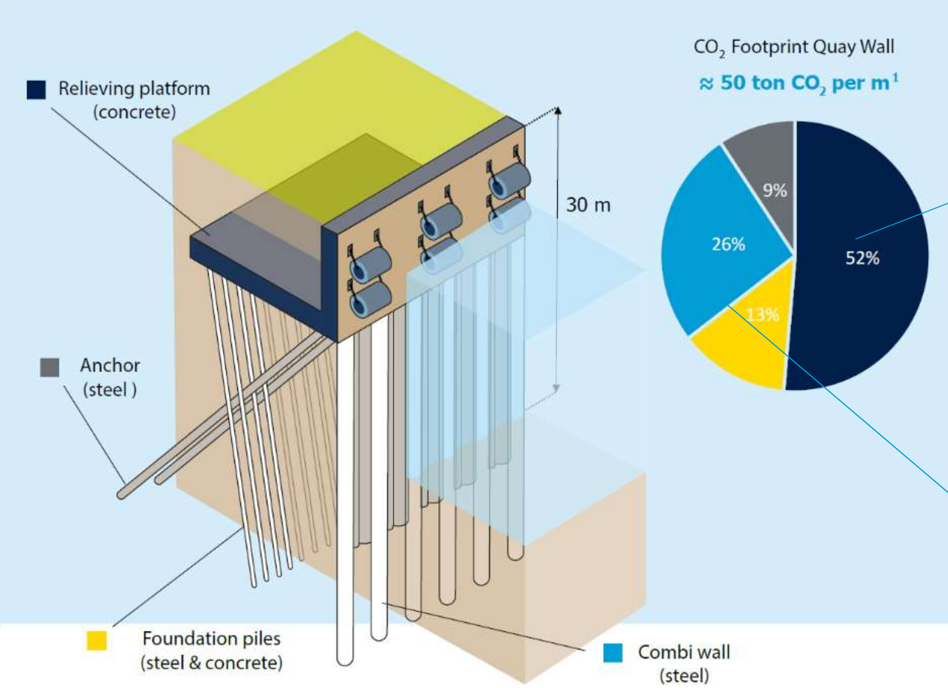
Vision & Ambition

New types of concrete

Existing structures

- Lifetime extension and optimize/maintain functionality.



Optimal use of steel materials

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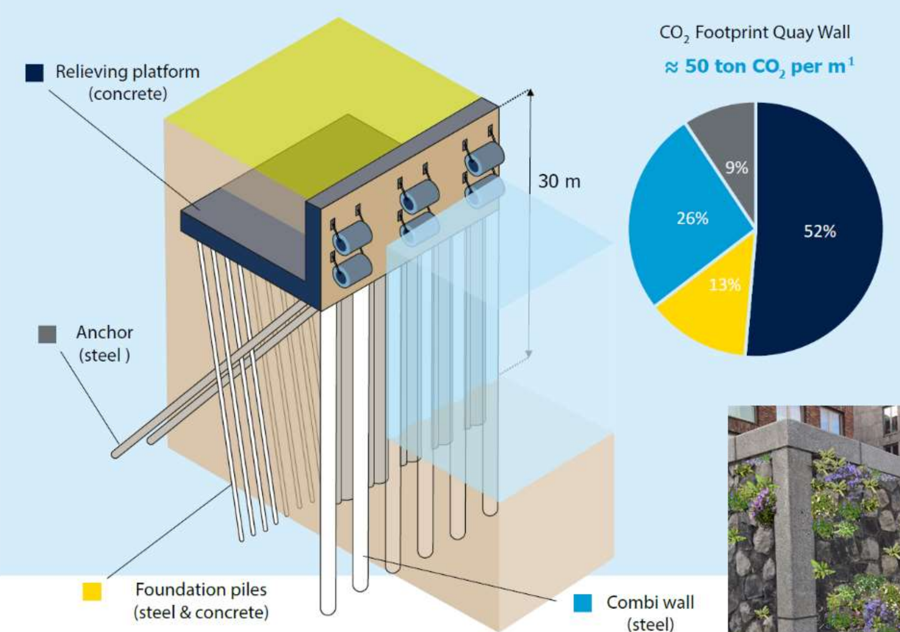
Vision & Ambition

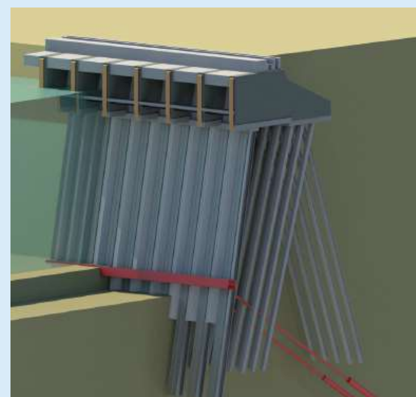
Existing structures

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



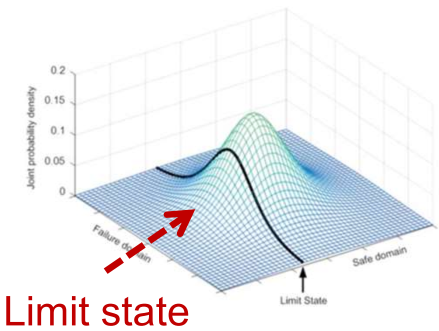
New marine structures

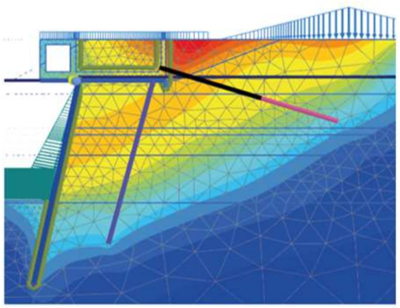
- 2023 - @2035@ => **Upgradeable** / **adaptive**
- @2035@ - 2050 => **Circular** / **modular** / **“green”**



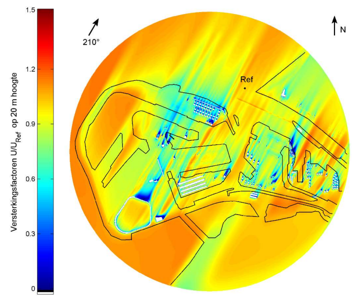
Main trends in quay-wall engineering

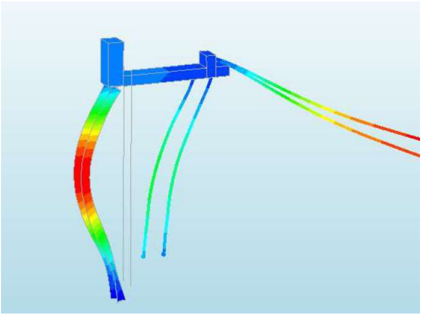
1) Reliability-based assessments



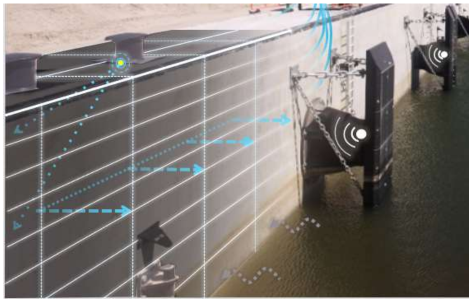


2) Advanced modelling & new methods



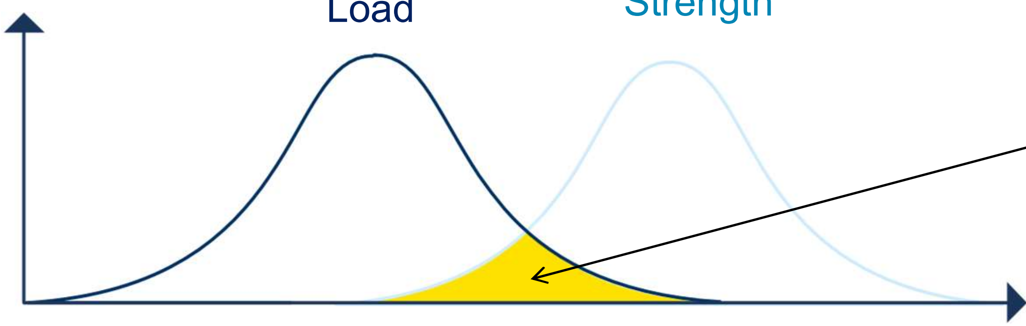


4) Sensoring & digitisation

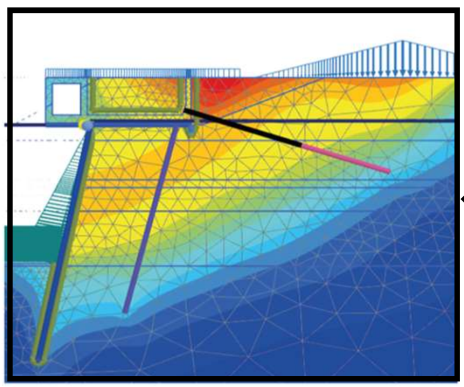


3) Full scale field tests / stress testing

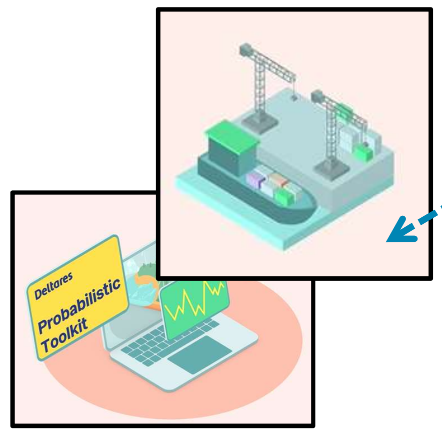
1) Reliability-based assessment: Probability of failure?



Finite element model



Probabilistic toolbox



Open-source library with statistical methods

- Prob2B®
- Probana ®
- Deltares Toolkit

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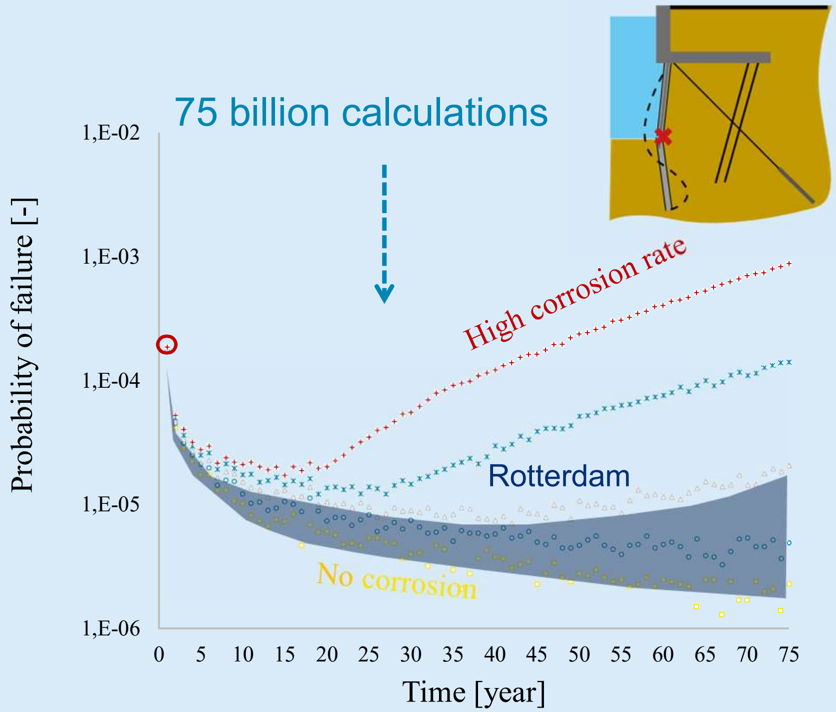
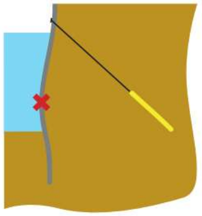
1) Reliability updating & past service performance

- 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



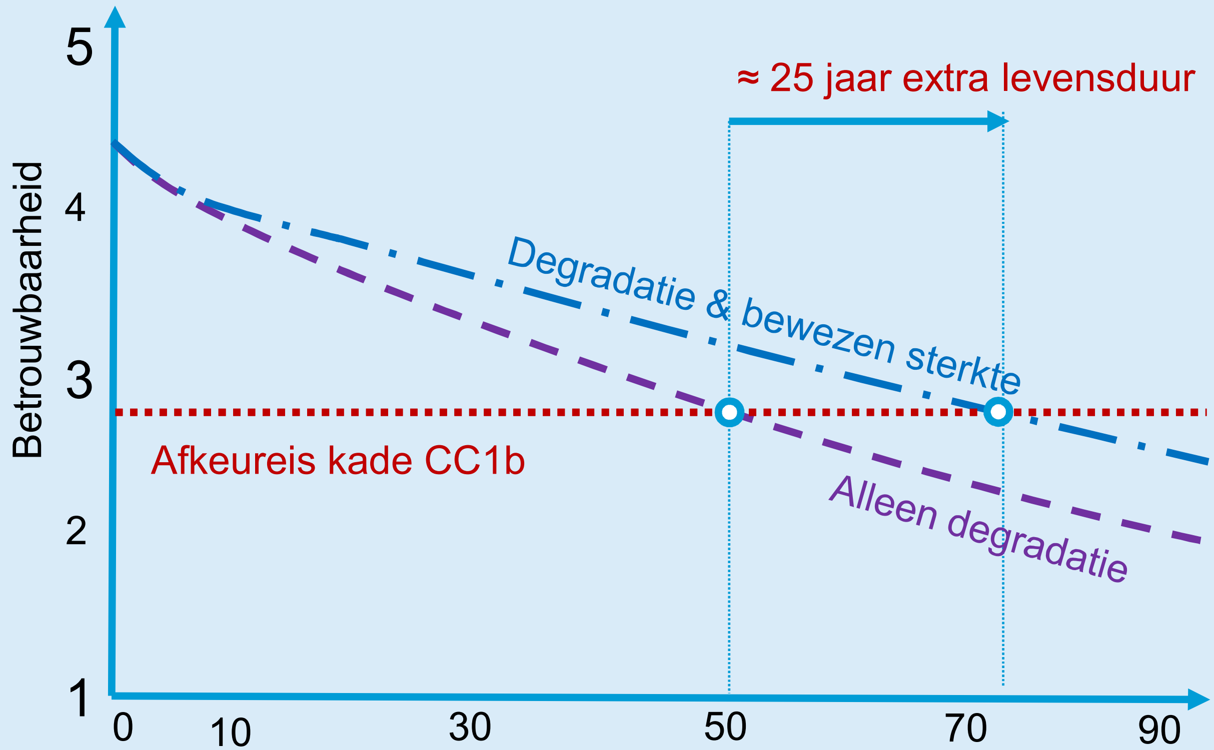
1) NEN "past service performance" (2023-2024)



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)



TNO innovation for life

Deltares

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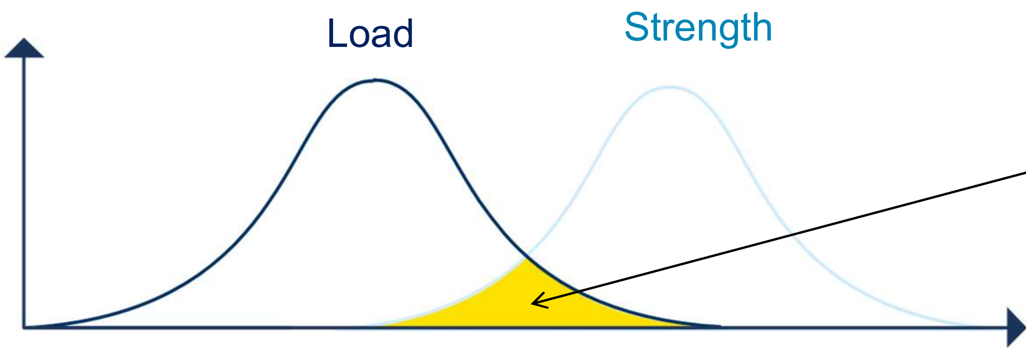
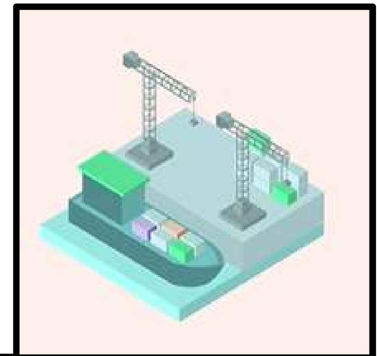
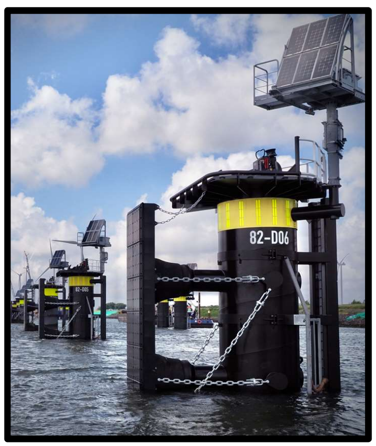
1) Reliability-based assessment: Probability of failure?

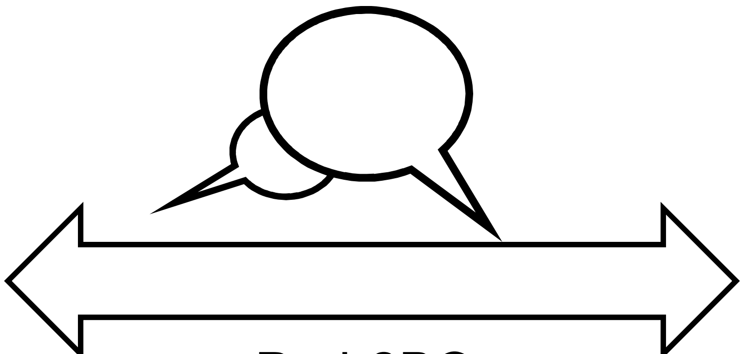


Probabilistic toolbox



P-Y curves





- Prob2B®
- Probana ®
- Deltares Toolkit

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1) Reliability-based assessment flexible dolphin

- Reference design D=ø2400mm; L=48m)
- AIS vessel data (actual displacement)
- Measurements berthing velocity

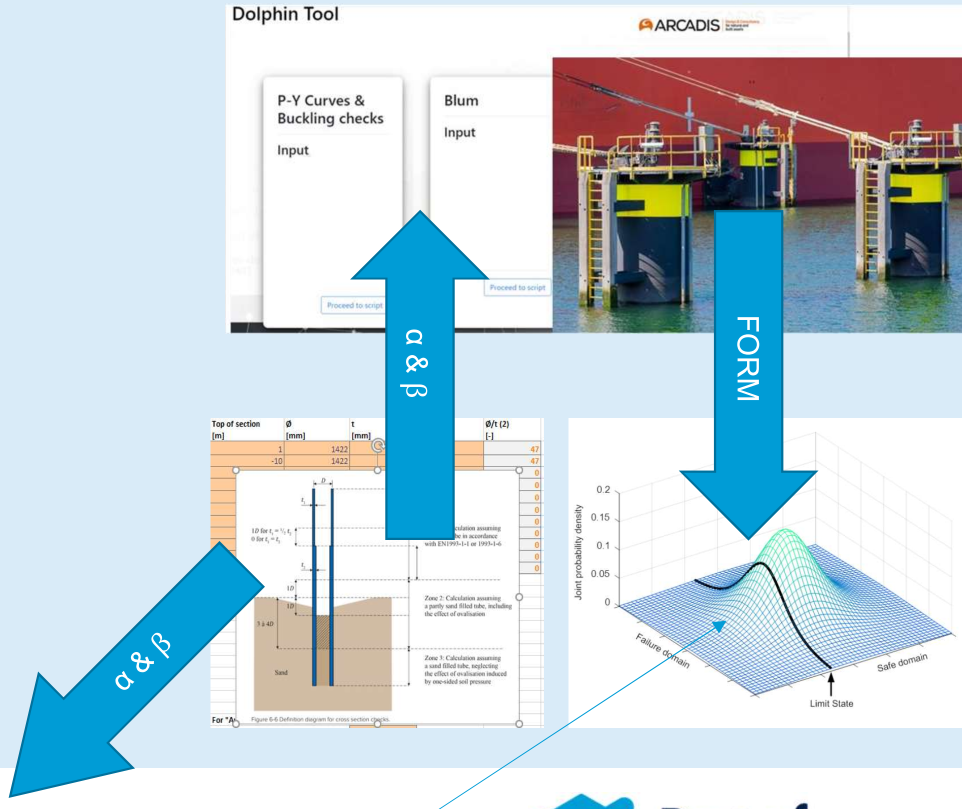
Preliminary results

- Reference design => $\beta_{design} \approx 3.59$.
- Update using data => $\beta_{update} \approx 4.87$.

⇒ Calculation time about 3 days

⇒ Lifetime extension/ bigger vessels

Automated dolphin design tool



Limit state function

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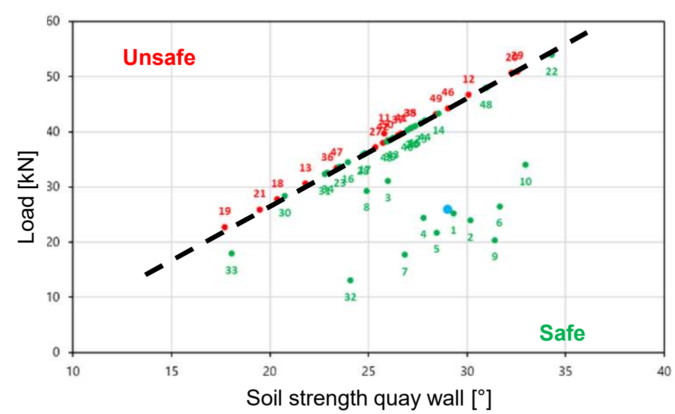
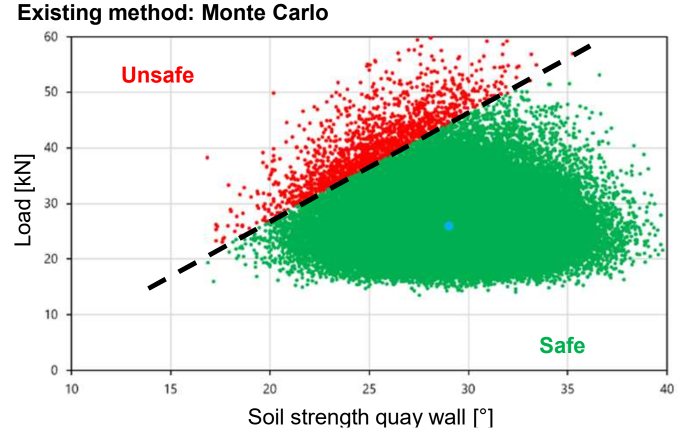
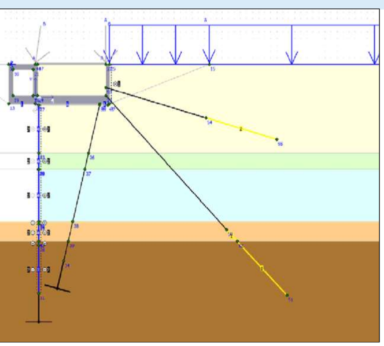
1) Geotechnical Reliability Analysis for Practical Applications (GRAPA)

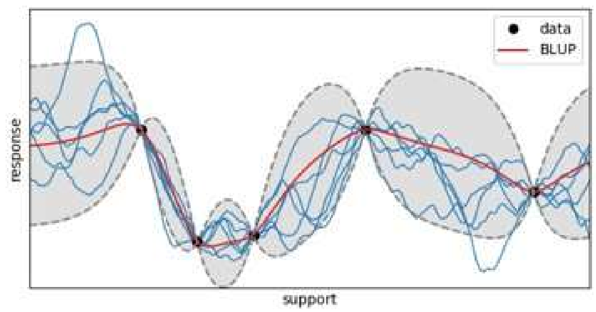


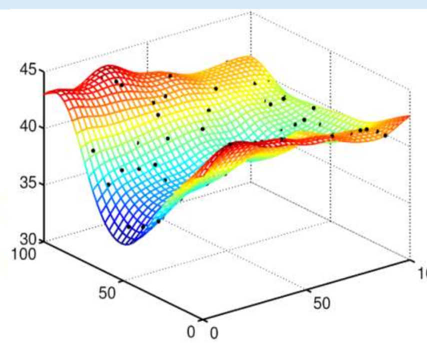
- Robustness reliability-based assessment using FEM
- Failure respond surface (kriging).
- ≈ 40 deterministic Plaxis calculations.

⇒ 10 times faster



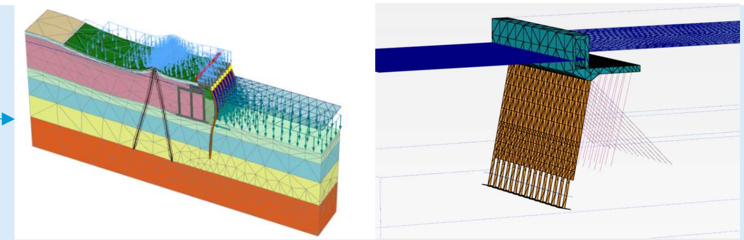


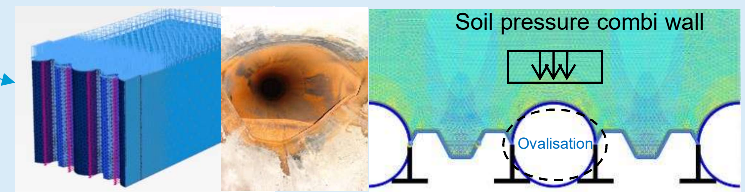


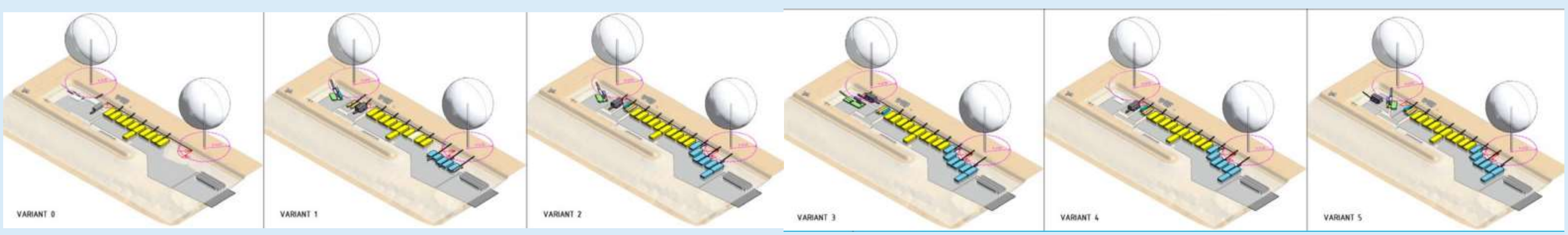


2) Advanced modelling & new methods

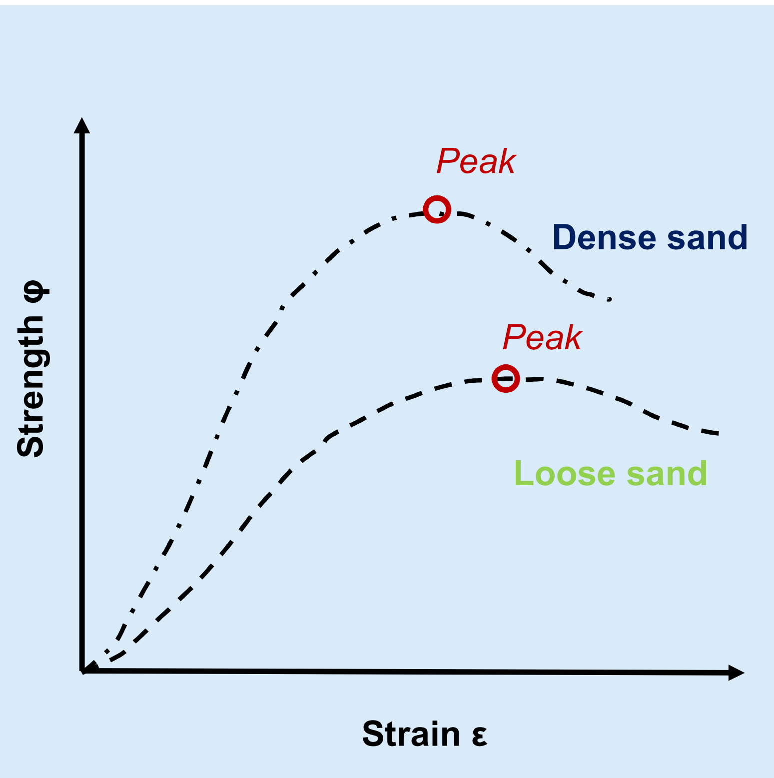
- New soil models (FEM 3D).Combining structural and geotechnical models.
- Local buckling of open steel tubes
- Generative design.
- Implementation of sensor data.





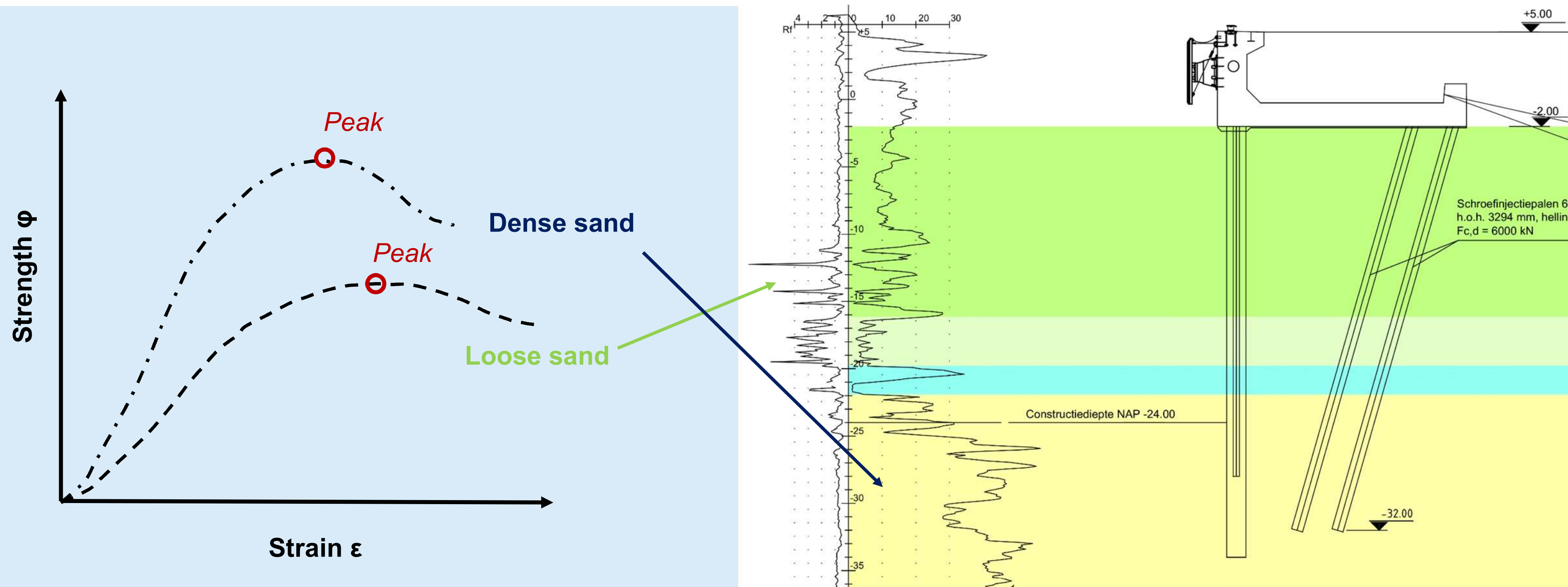


2) Strain-dependent capacity

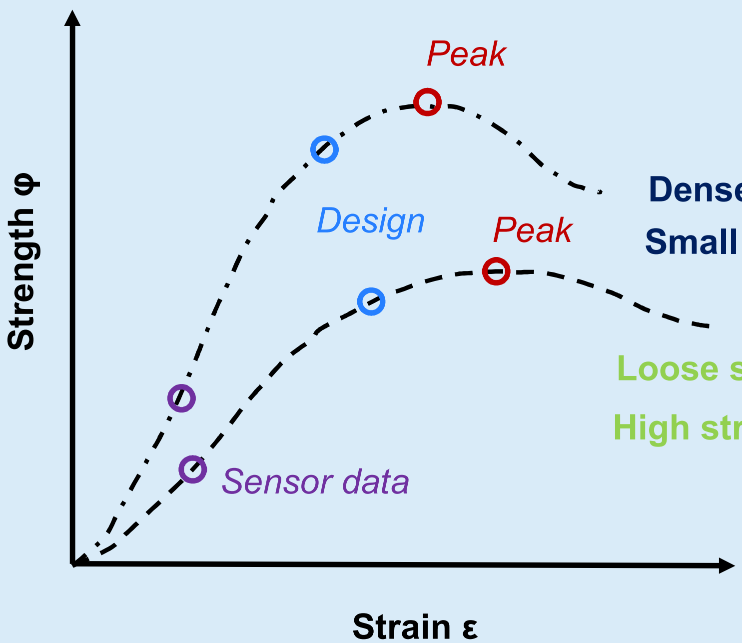


Triaxial test

2) Strain-dependent capacity



2) Strain-dependent capacity

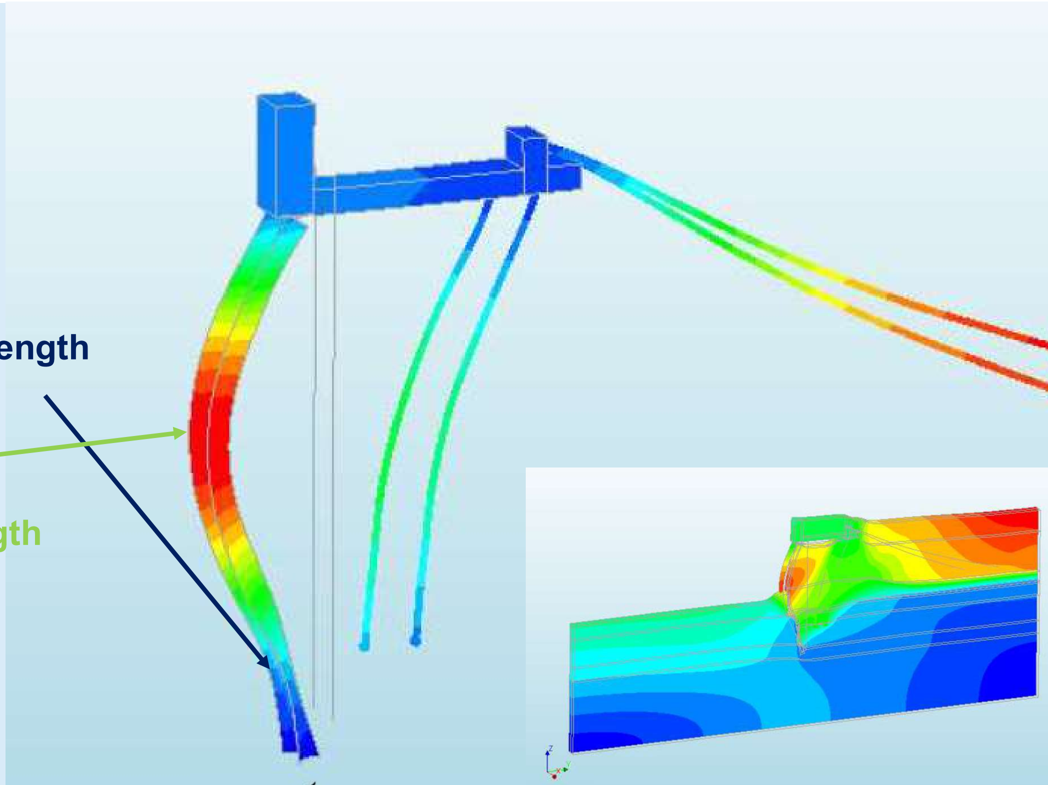


Dense sand

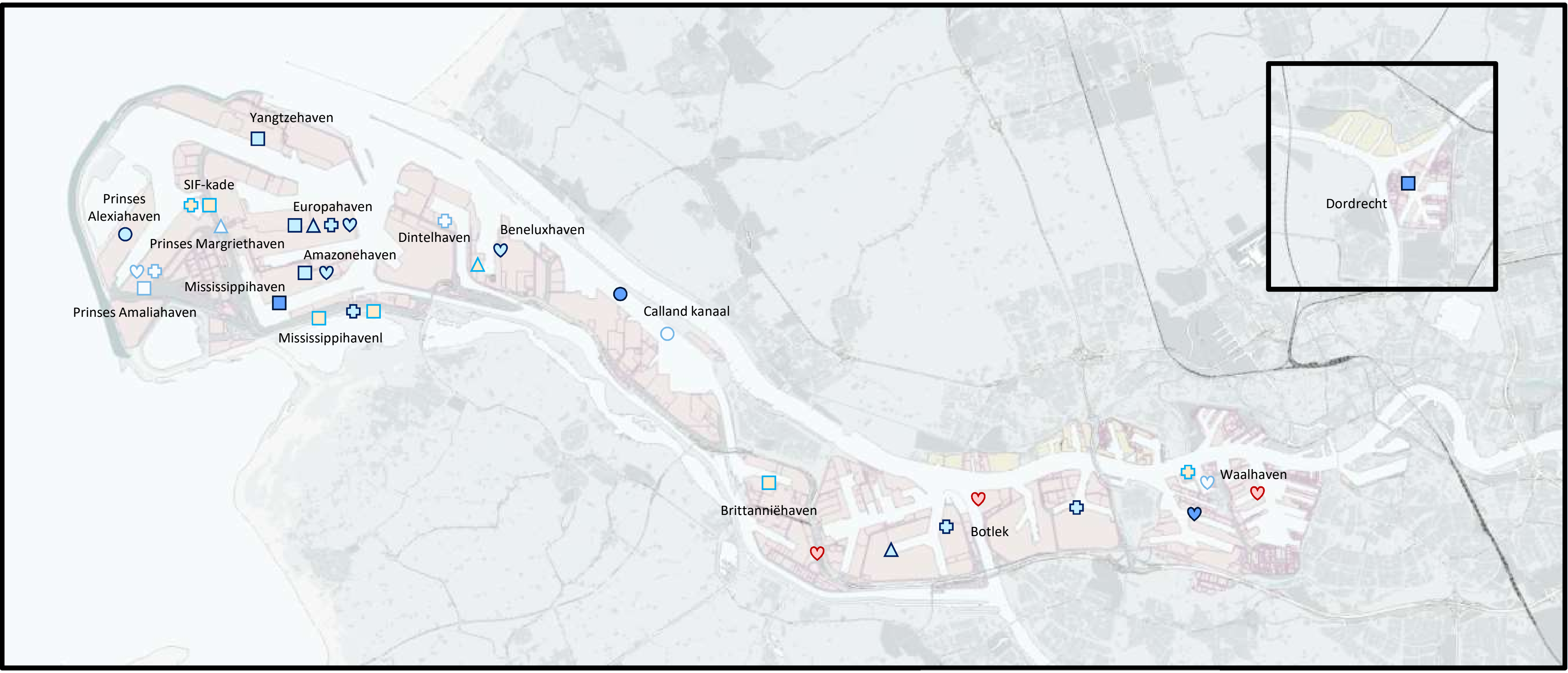
Small strain => high strength

Loose sand

High strain => high strength



3) Sensoring & digitization



Smart quay wall | Quick Release Hook | Impressed current | Shore Power | Other

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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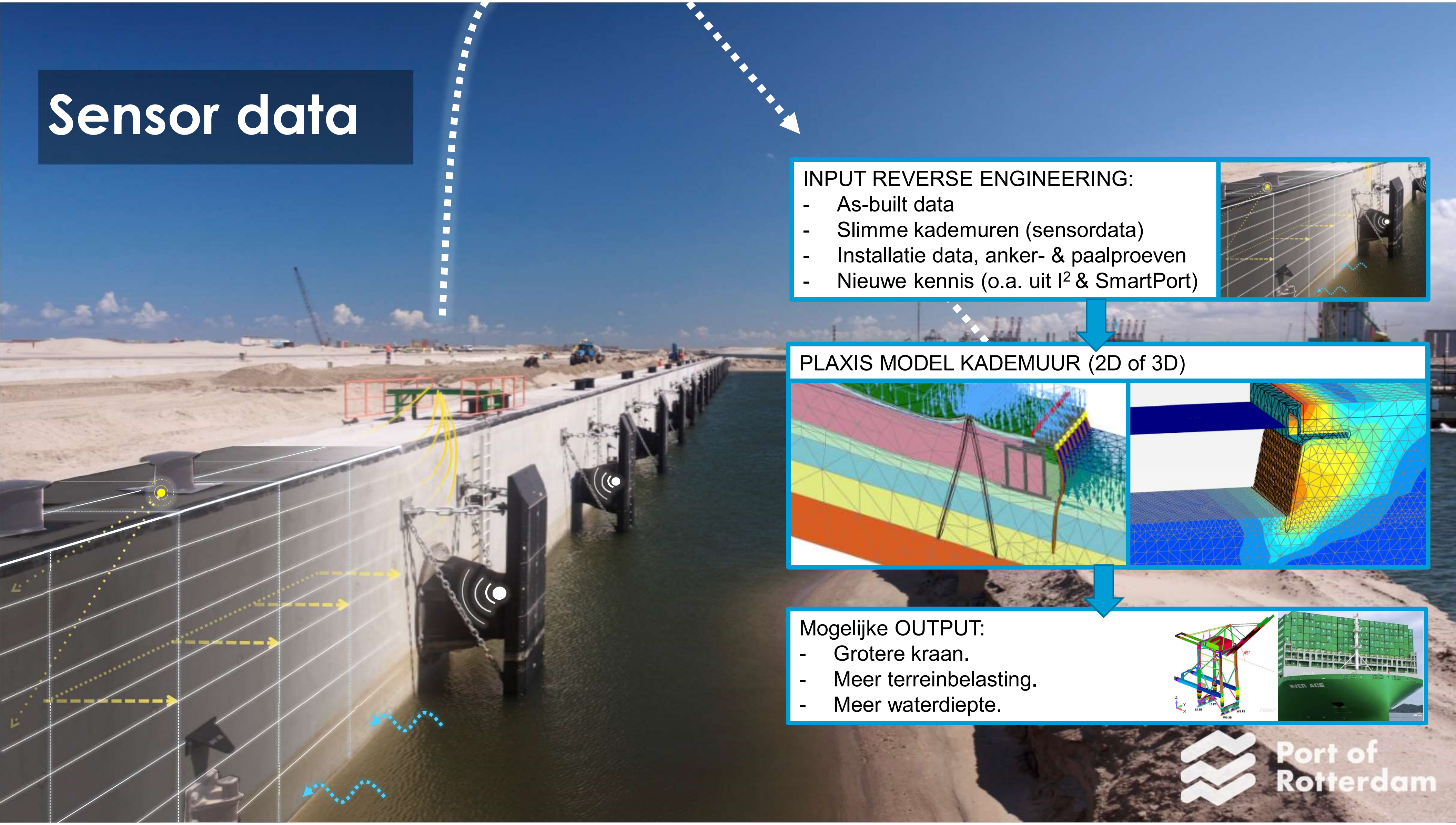
Sensor data
INPUT REVERSE ENGINEERING:
- As-built data
- Slimme kademuren (sensordata)
- Installatie data, anker- & paalproeven
- Nieuwe kennis (o.a. uit I² & SmartPort)
PLAXIS MODEL KADEMUUR (2D of 3D)
Mogelijke OUTPUT:
- Grotere kraan.
- Meer terreinbelasting.
- Meer waterdiepte.
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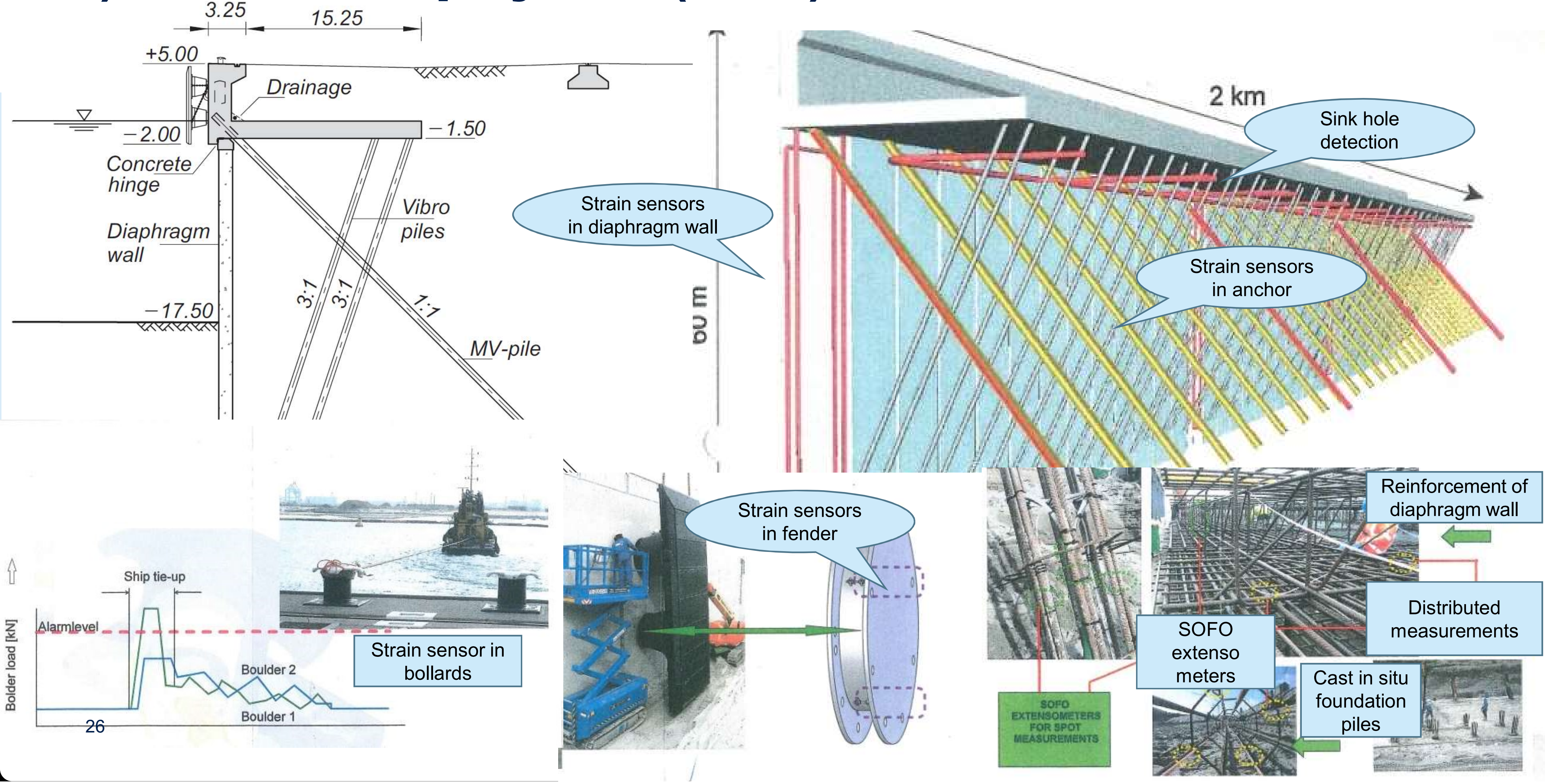
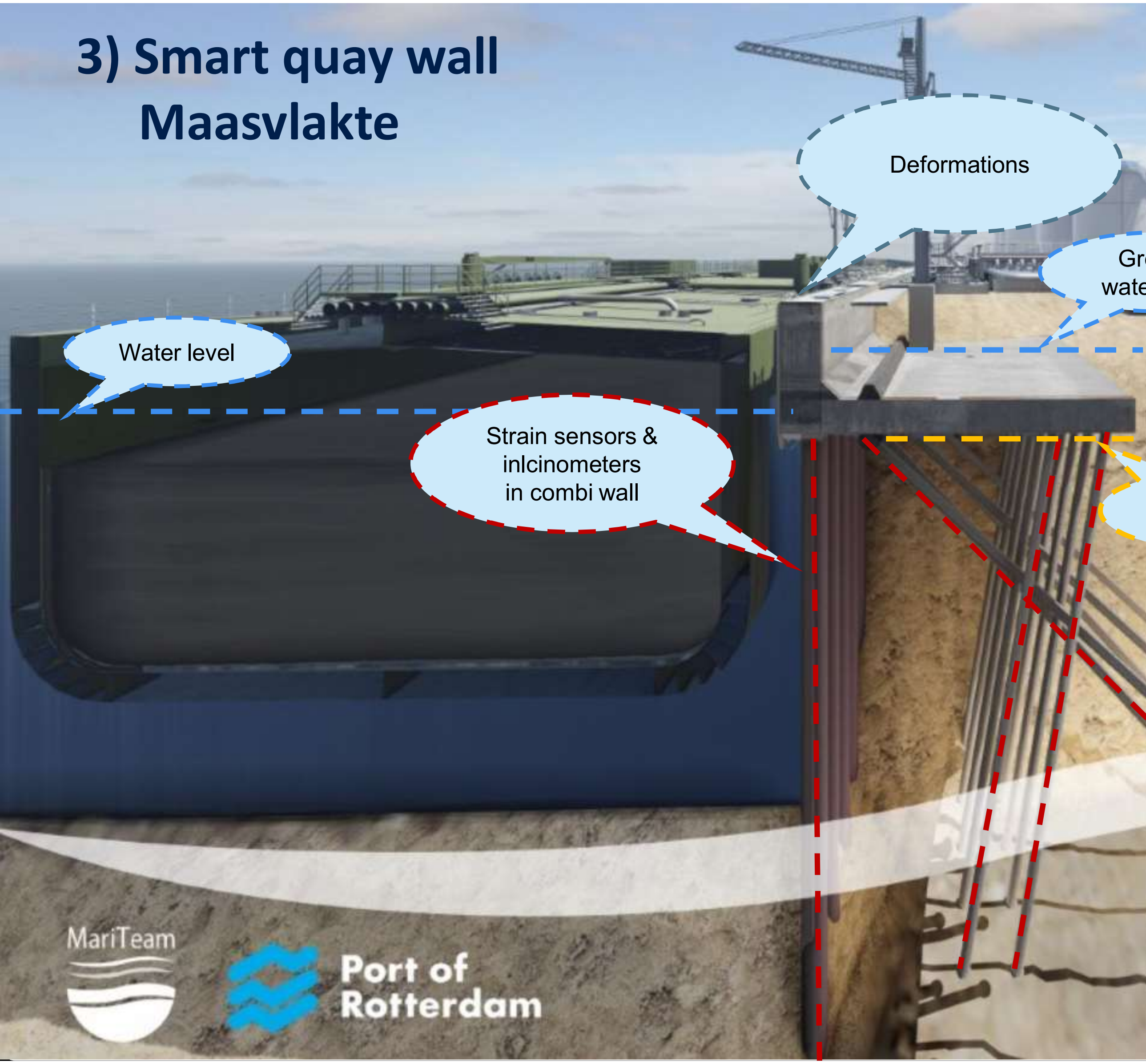
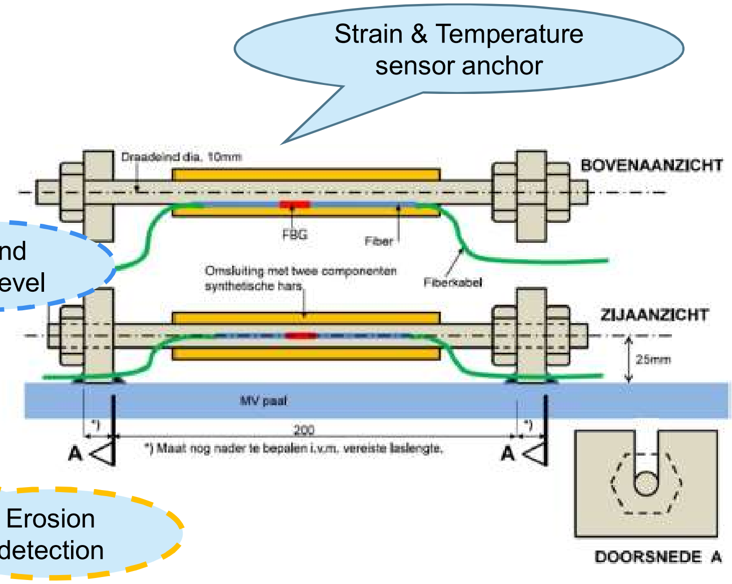
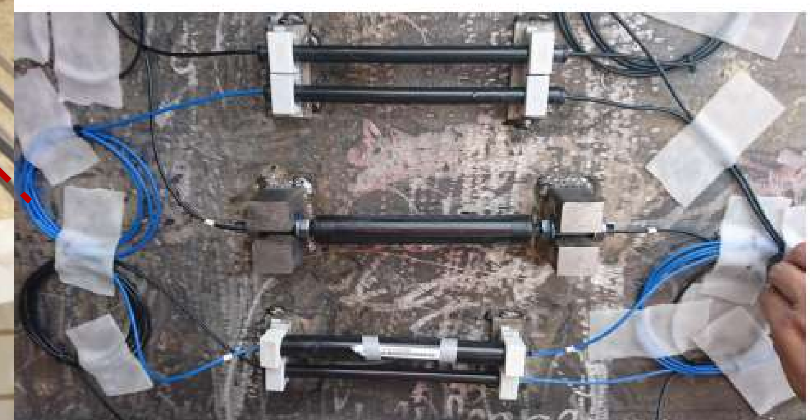
3) First smart quay wall (2008)



3) Smart quay wall Maasvlakte







MariTeam

Port of Rotterdam

inventec b.v.

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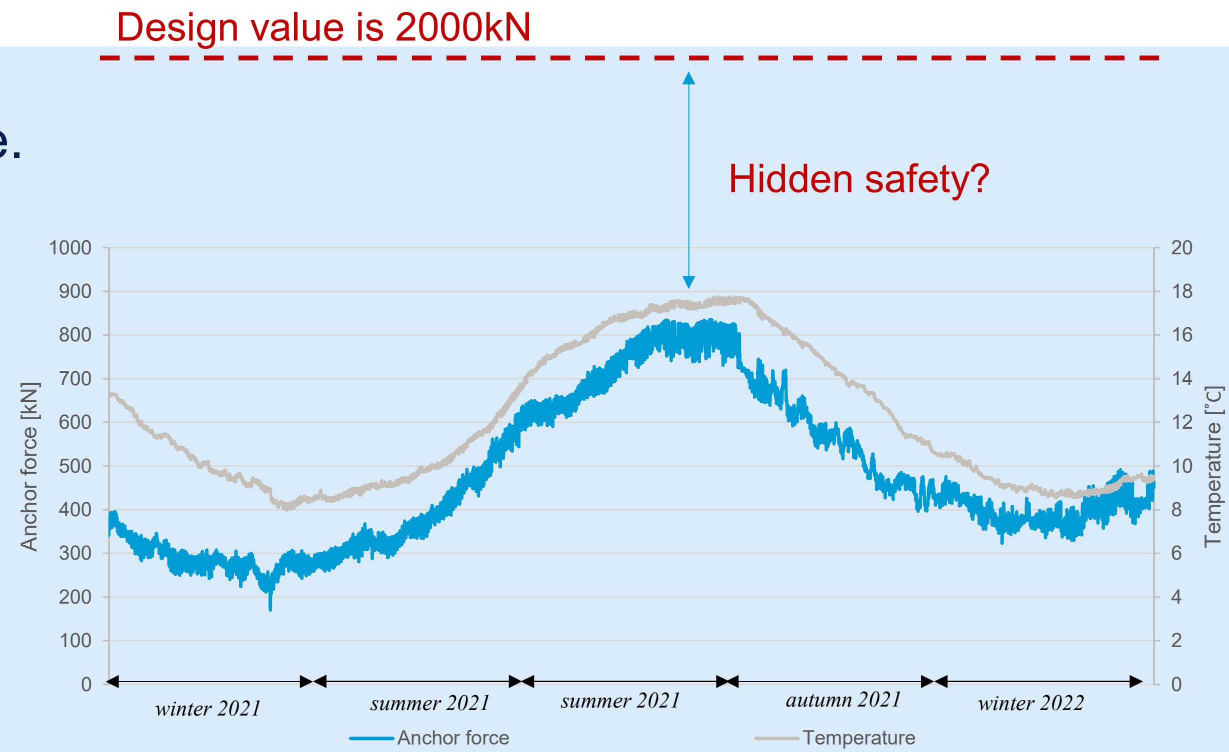
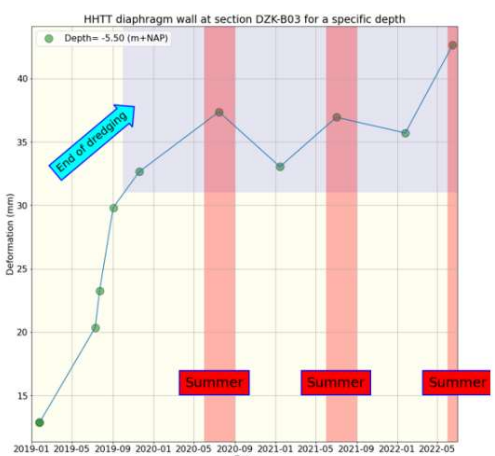
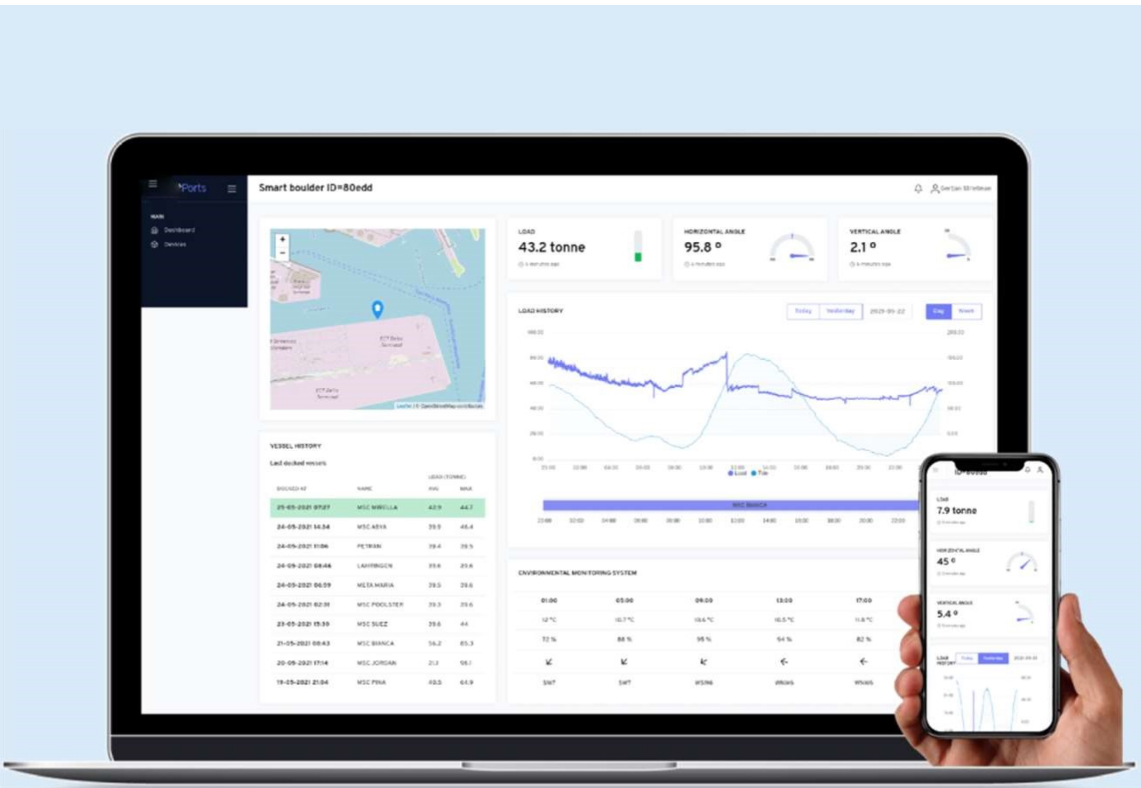
3) Smart quay walls: Anchor Force

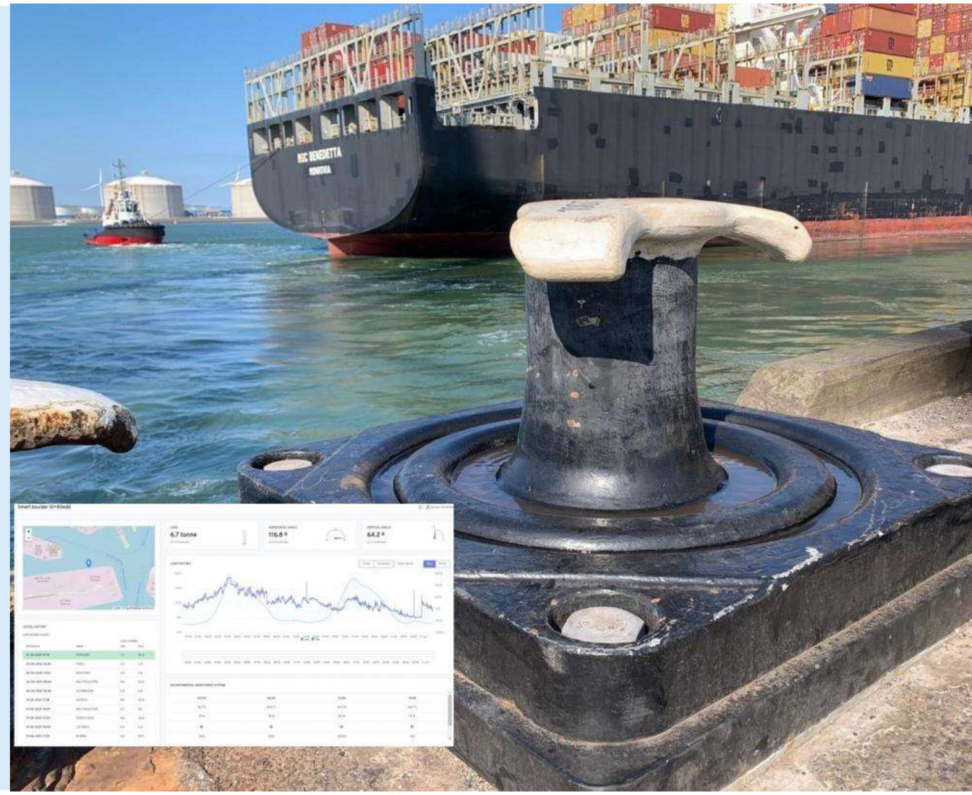
- Lower compared to design value.
- Reduce model uncertainty.
- Input for checking the influence of climate change on quay-wall behaviour.





3) Data analytics: Example Smart Bollard





STRAATMAN BV
Mooring & Dredging Equipment

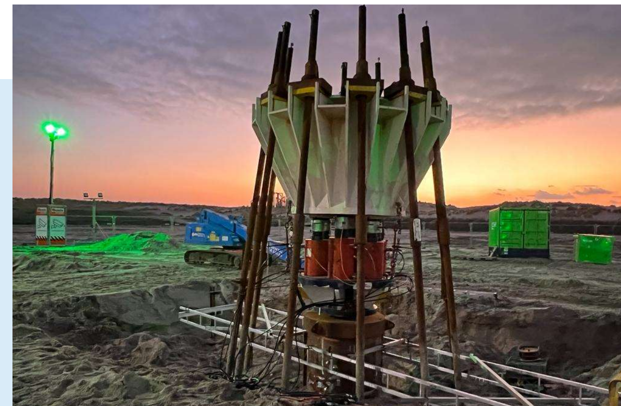
Port of Rotterdam

4) Testing bearing capacity open ended steel tubes

- Objective: Selection of design method (NEN, CUR of ISO method)
- Static vs cyclic loads.

Scope:

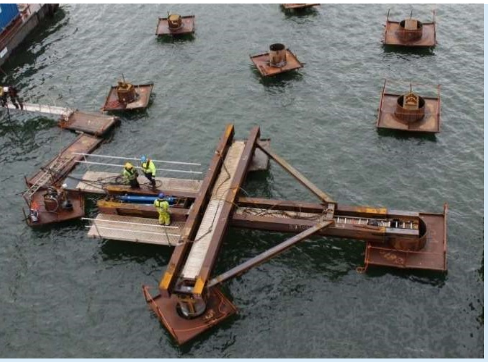
- 4 test piles ø1220 (D/t of 60, 80 and 100).
- Spider-shaped test frame for static test
- Tension frame for cyclic test.
- Advanced strain and pressure sensors.
- Max test load 25.000 kN/ 15.000 MN.
- Costs about €2.5m.



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

4) Full scale field tests & stress testing

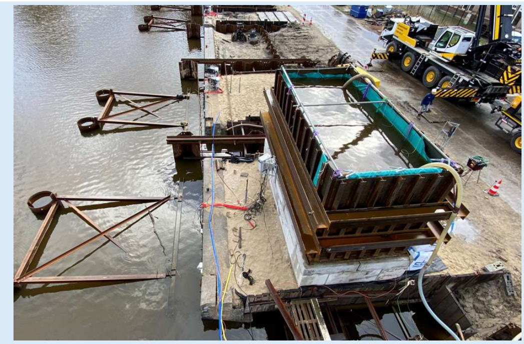
Flexible dolphin (2014)



Precast concrete piles (2017;'21)

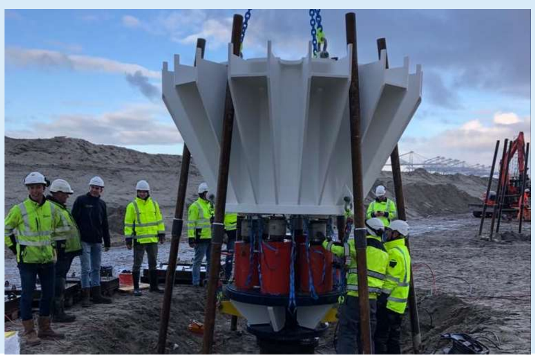
Sheet pile piles (2018)

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

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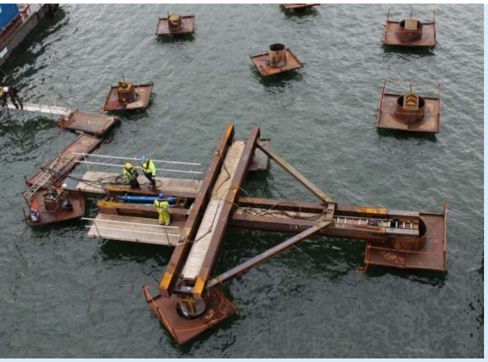
(2023/2024)

4) Full scale field tests & stress testing

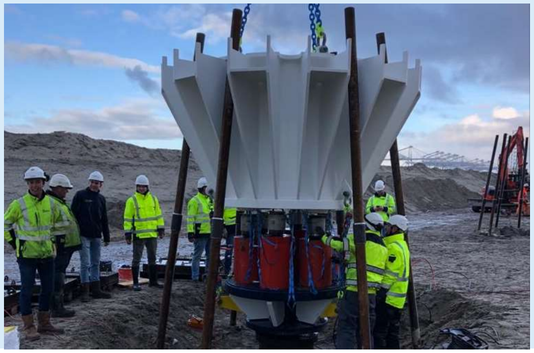
Flexible dolphin (2014)



Precast concrete piles (2017;'21)

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

Cast in situ piles (2020)



Project	n	Costs	Direct savings		Annual future savings[a]	
	[-]	[m€]	[m€]	[kton CO_2]	[m€]	[kton CO_2]
1) Dolphins 2014	8	0.75	6.10	0.25	6.00	0.30
2) Precast concrete 2017	4	0.45	0.55	0.75	n/a	n/a
3) Anchors 2017-2022	6	0.75	4.50	1.00	3.00	1.50
4) 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

Thank you for your attention.

PAO TECHNIEK EN MANAGEMENT

TU Delft

Port of Rotterdam

SMART PORT