

CROW Flexible dolphins

Alfred Roubos / Port of Rotterdam Authority / TU Delft
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Alfred Roubos



- Port Engineer (17.5 years) Port of Rotterdam Authority
- Lecturer PAO (2010)
- Researcher TU Delft (2016);
- Doctoral defence Oct. 2019.
- Member of several national & international committees (CEN, NEN, CROW, PIANC, BS)

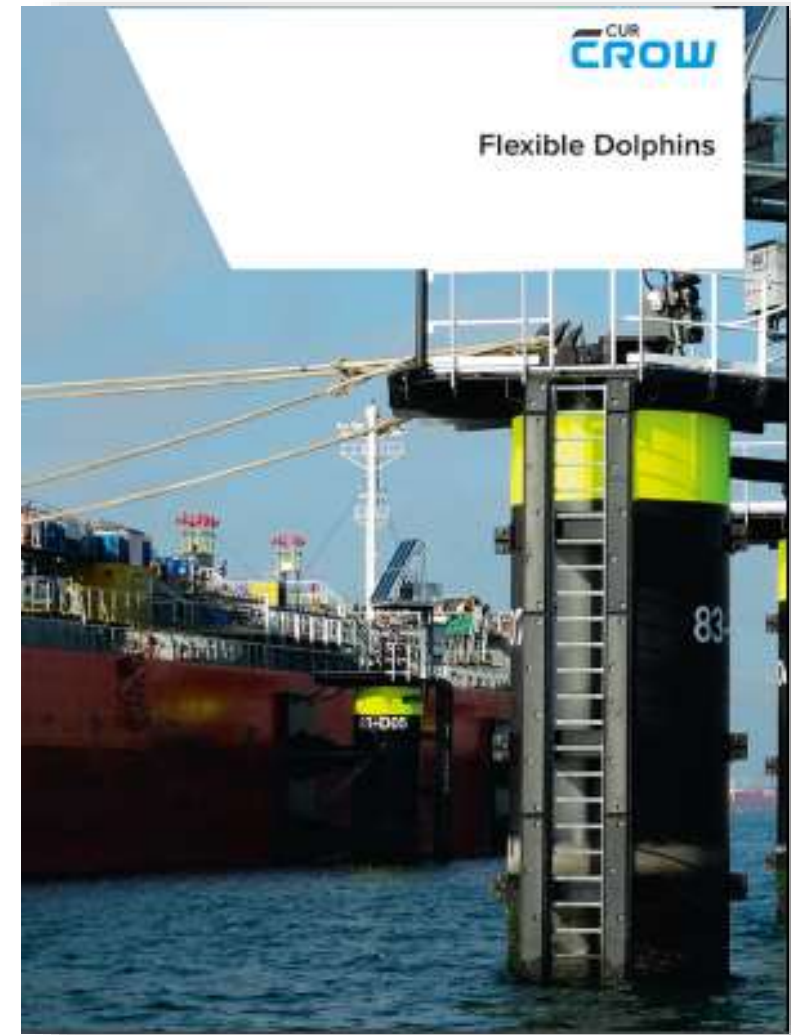
Main interests:

- Marine structures (e.g. quay walls, jetties and flexible dolphins)
- Dredging, revetments and bottom protections
- Innovations, research & full scale field tests

Content

1. Introduction & motivation
2. Upgrade CROW guideline
 - Berthing energy and mooring loads
 - Modelling flexible dolphins
 - Tests
 - Design approach
3. Impact of the new CROW guideline

Questions & discussion (10 min)





What is a flexible dolphin?

≈ 4.755 in Rotterdam, 693 assets owned by PoR ; €60.000,- to €300.000,- per pile

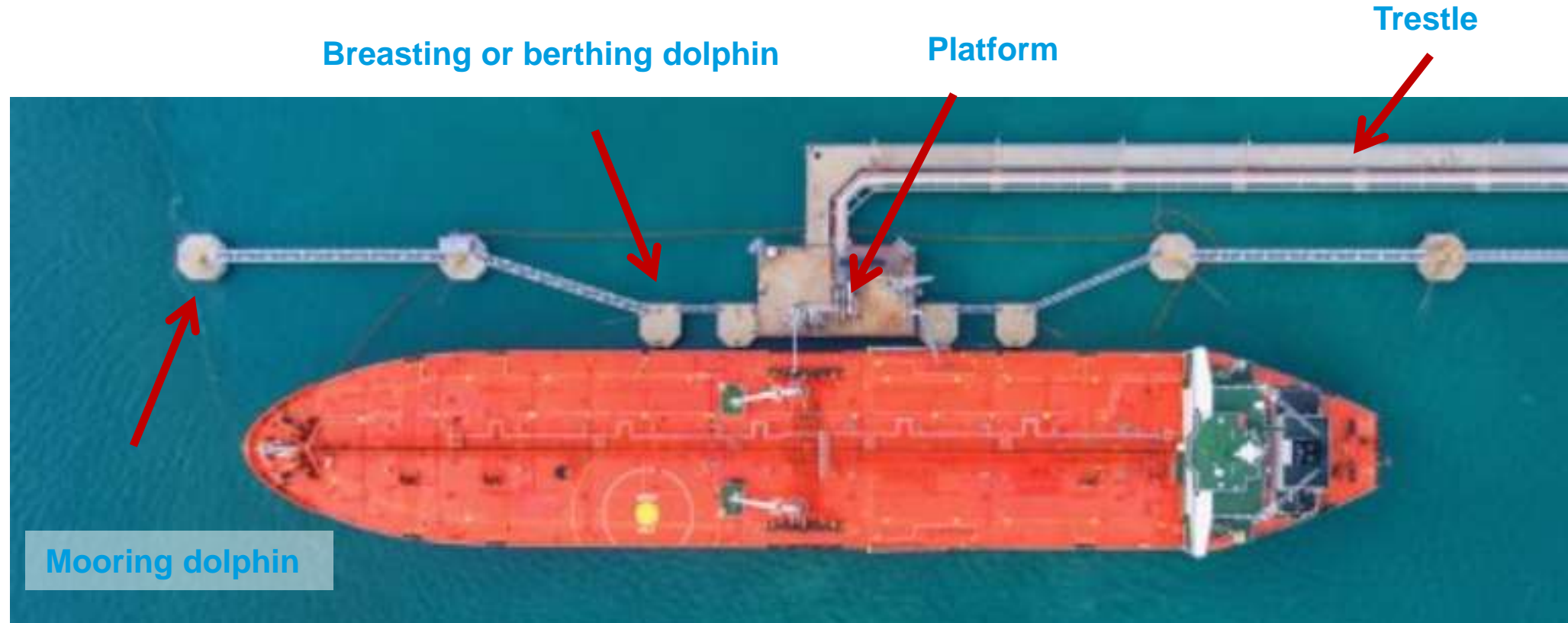
**Breasting & mooring dolphins,
slackening structures & crash barriers.**



Functions:

1. Absorb berthing energy.
2. Transfer mooring loads.
3. Protection of vessel.
4. Protection of jetty.

Typical layout jetty



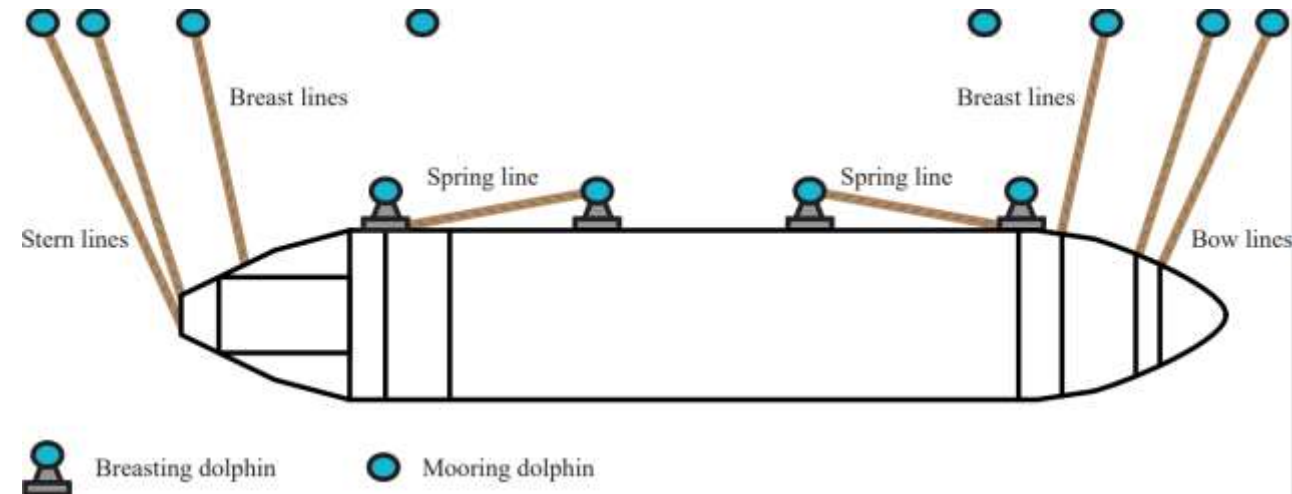
What is a flexible dolphin?

- Horizontally loaded flexible dolphin.



Breasting dolphins absorb berthing energy and mooring line forces.

Top view berth layout consisting of flexible dolphins

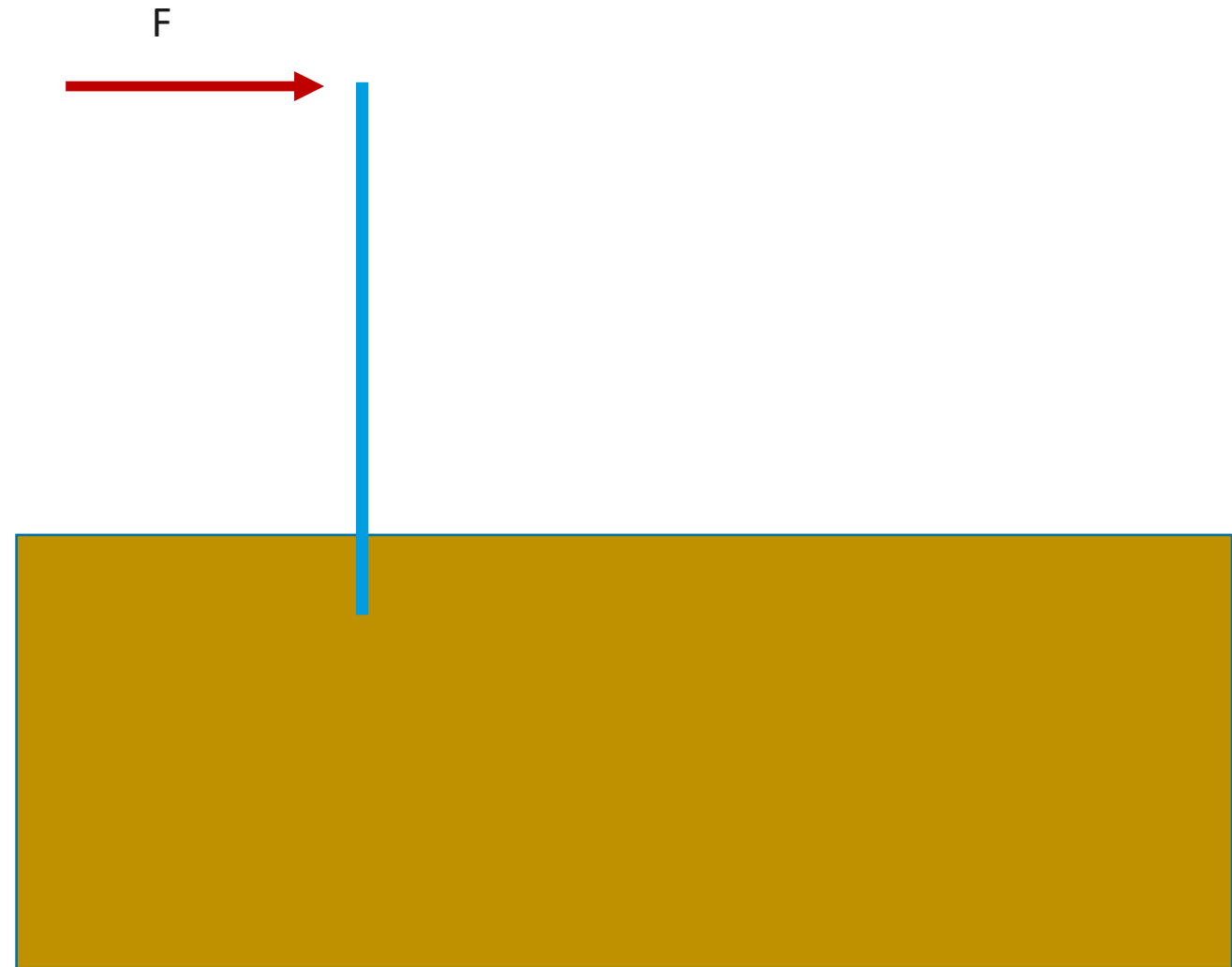




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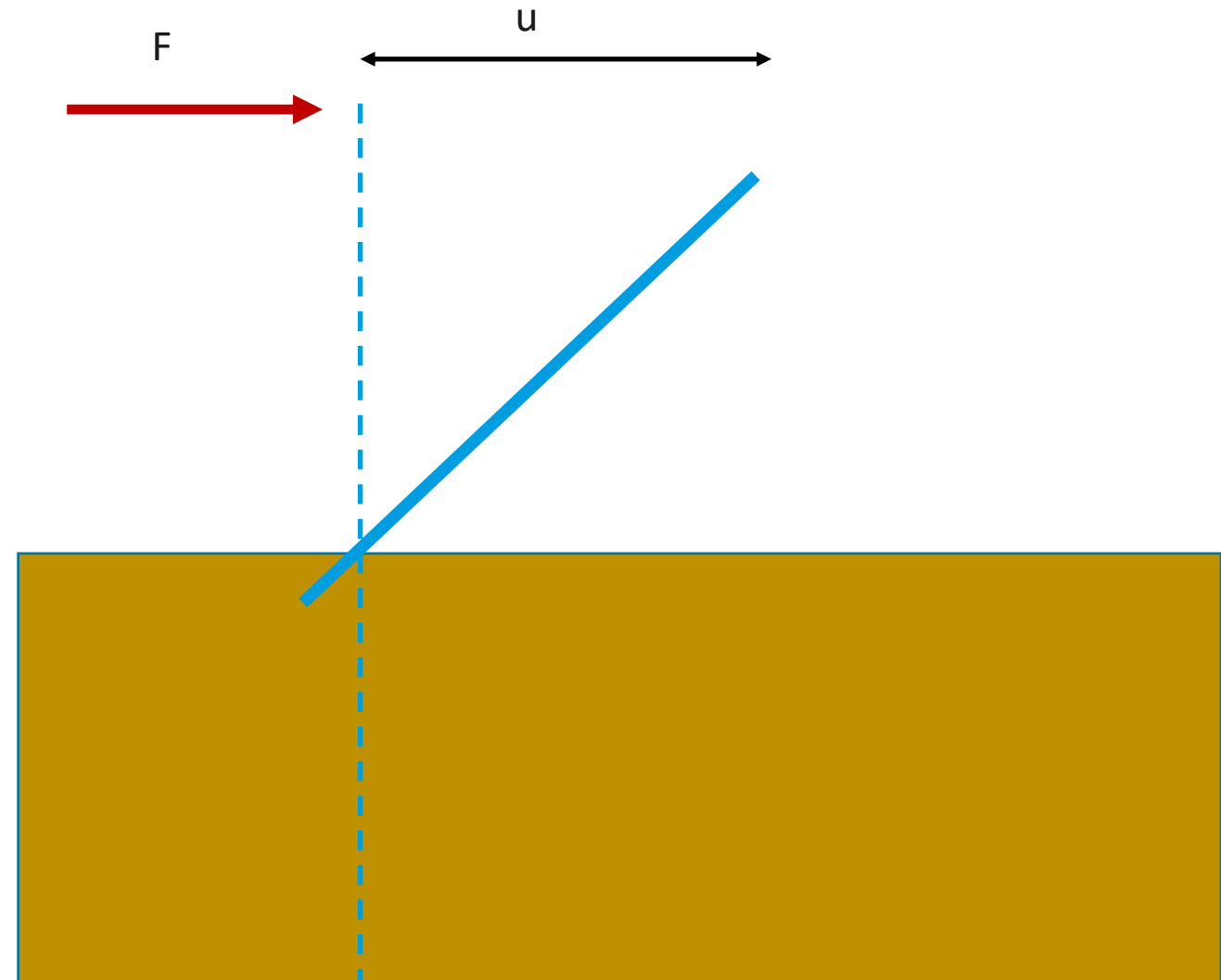
What is a flexible dolphin?

- Horizontally loaded flexible dolphin.



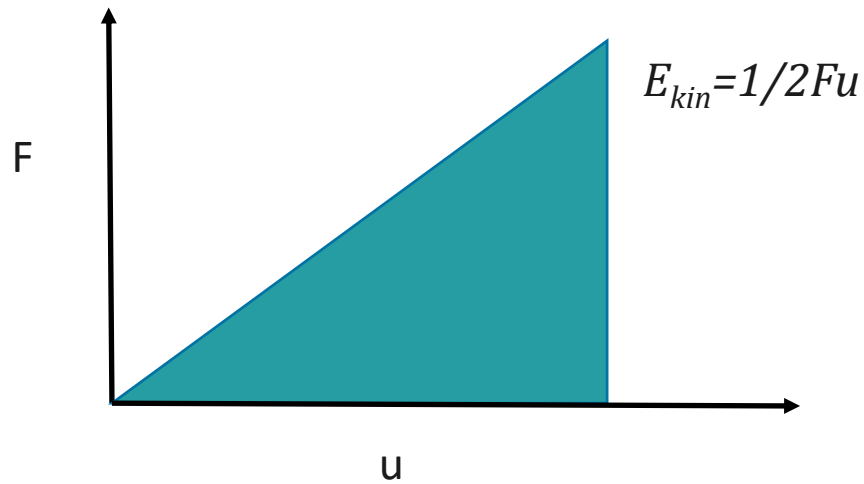
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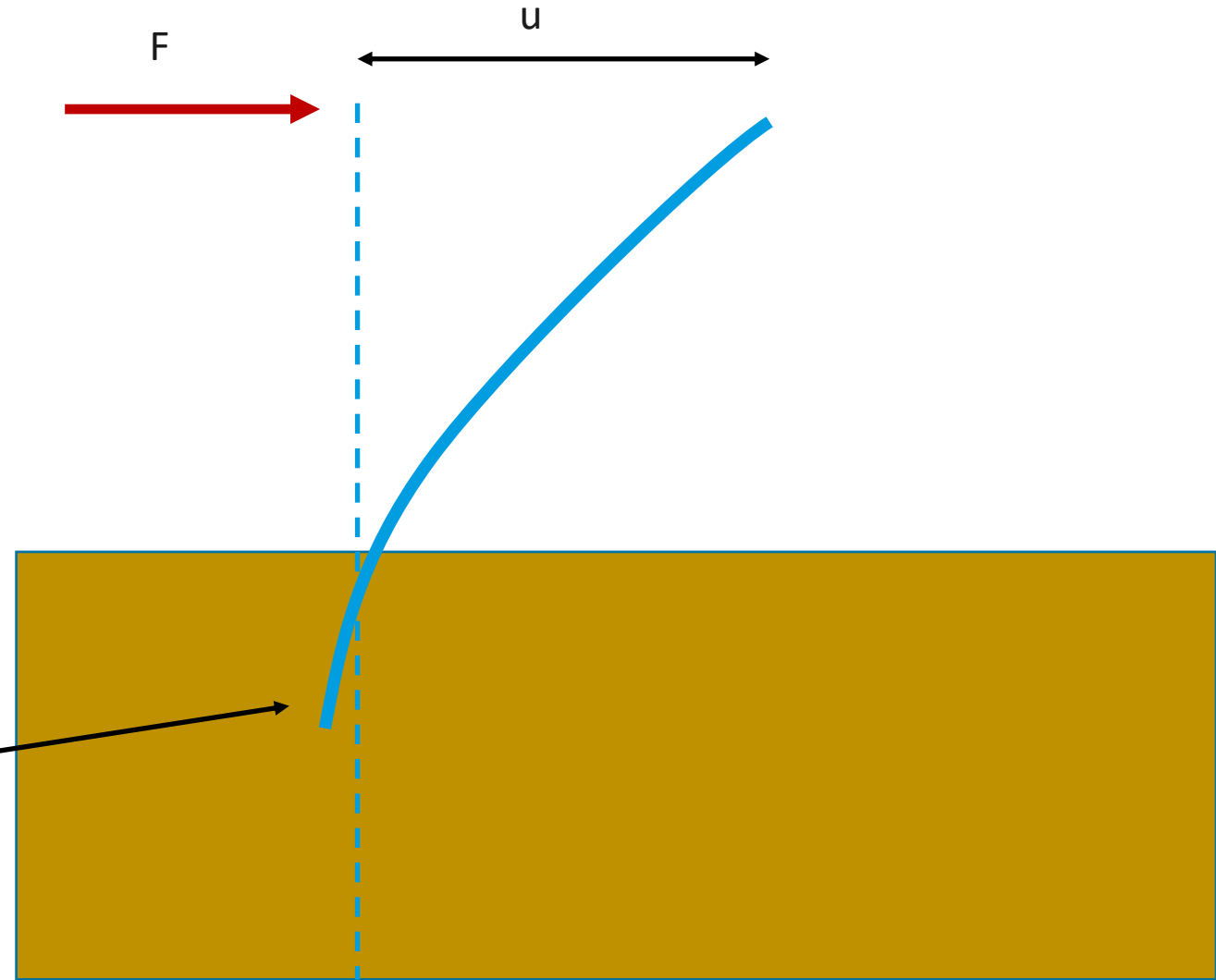


What is a flexible dolphin?

- Horizontally loaded flexible dolphin.

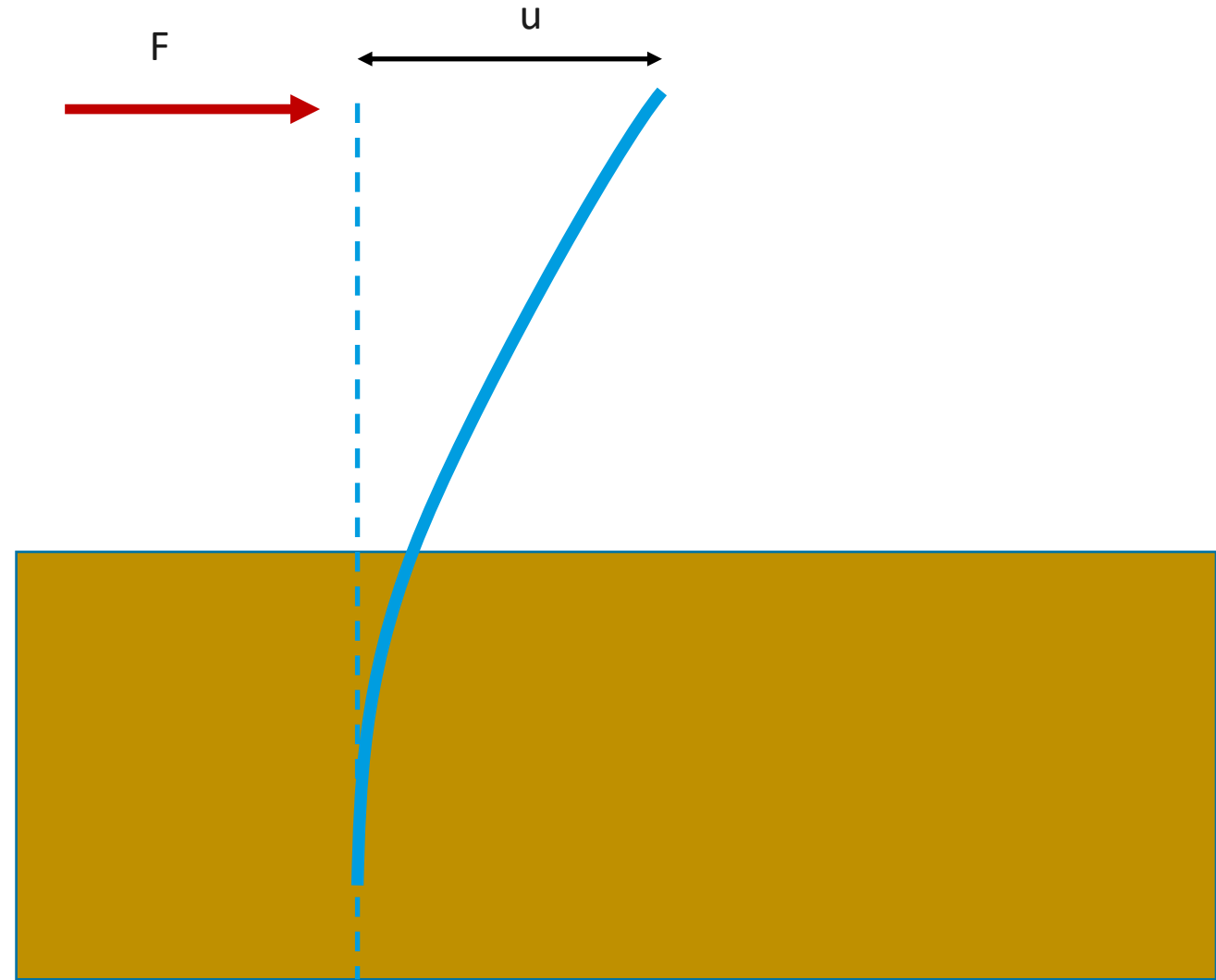
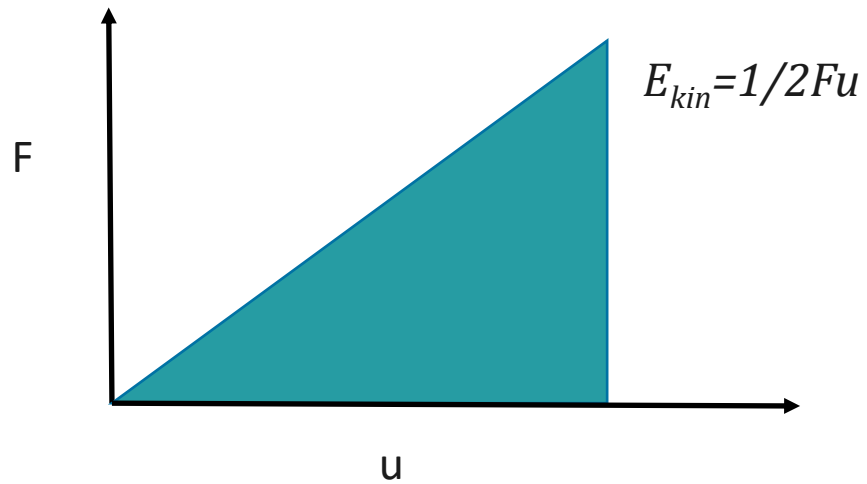


When a dolphin pile is too short, this results in (permanent) displacement of the pile toe and this displacement contributes to absorbing berthing energy.



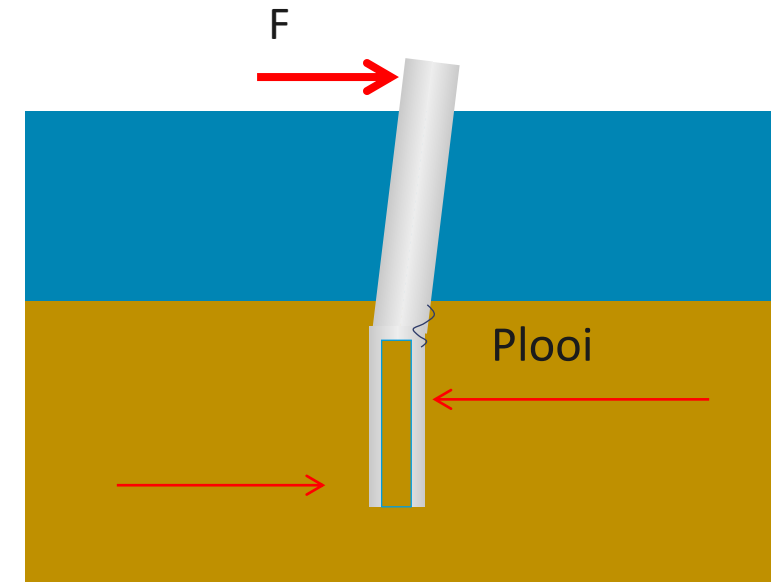
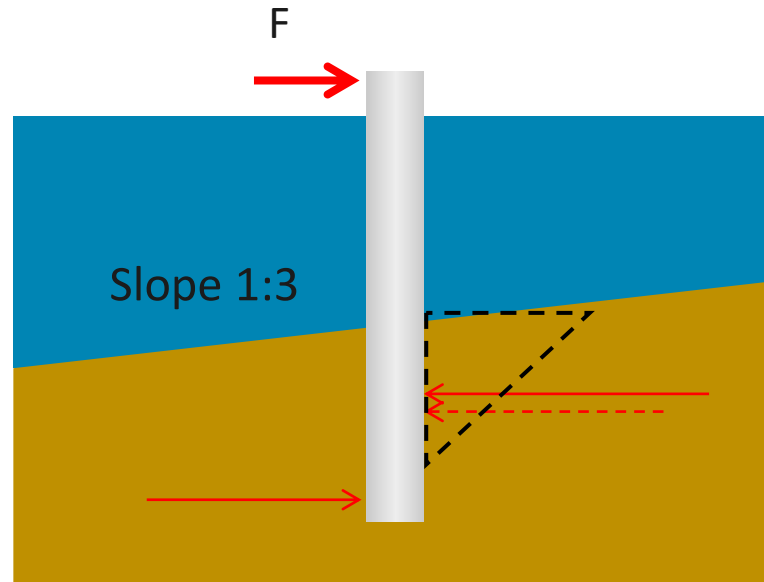
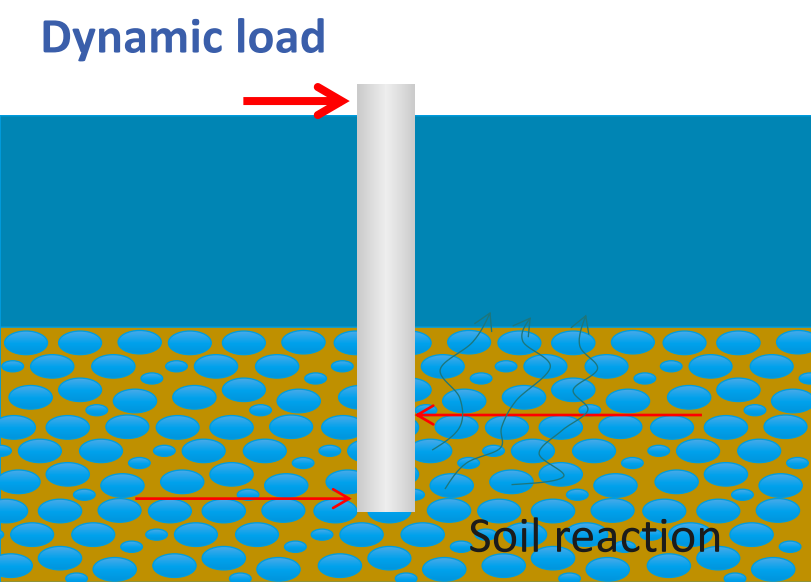
What is a flexible dolphin?

- Horizontally loaded flexible dolphin.



What is a flexible dolphin?

- Static versus dynamic soil behaviour
- Effects of sloping seabed
- Local buckling



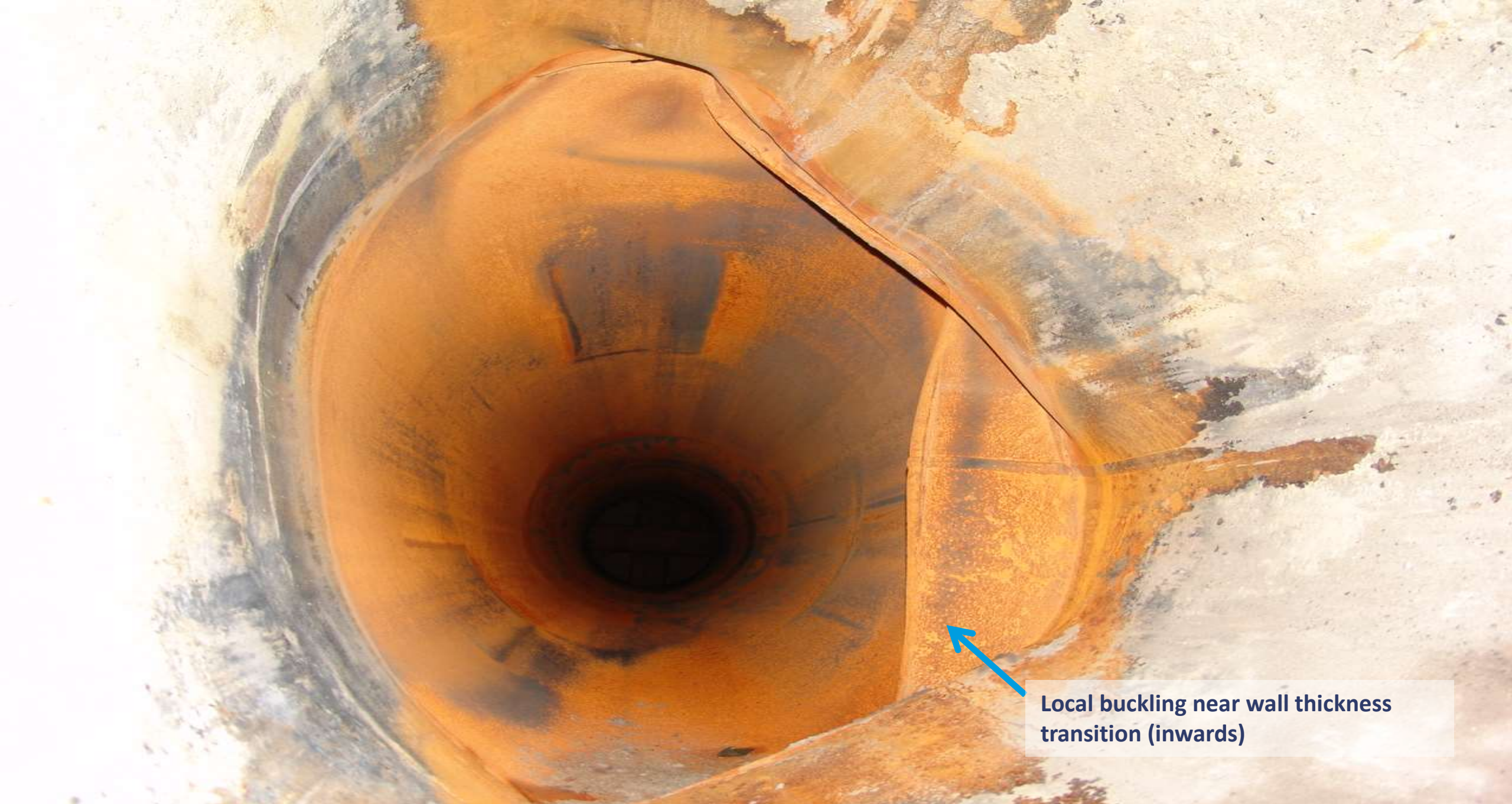


Local buckling empty tube (inwards)



Local buckling sand filled tube (outwards)

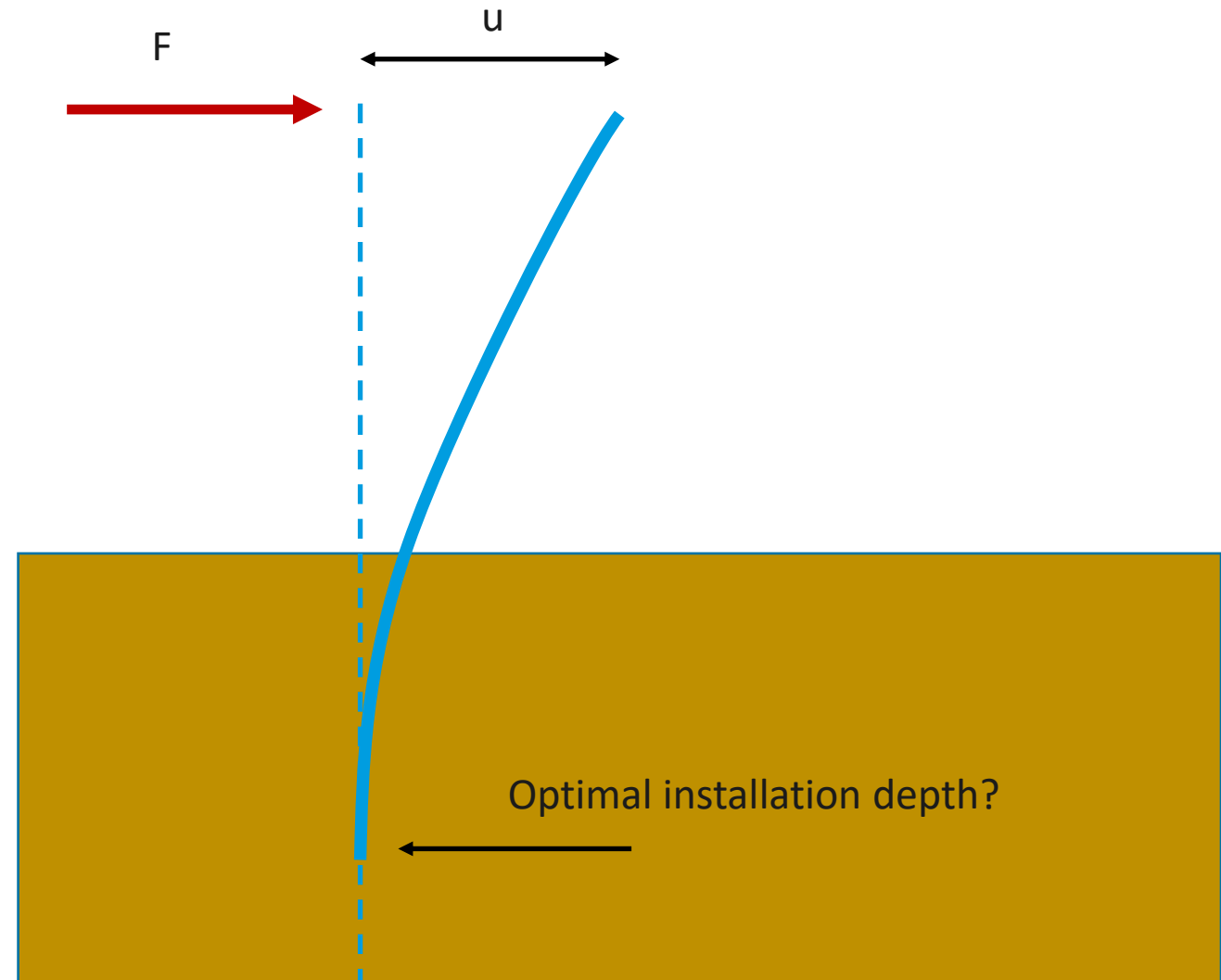




Local buckling near wall thickness transition (inwards)



First CROW design guideline in 2017

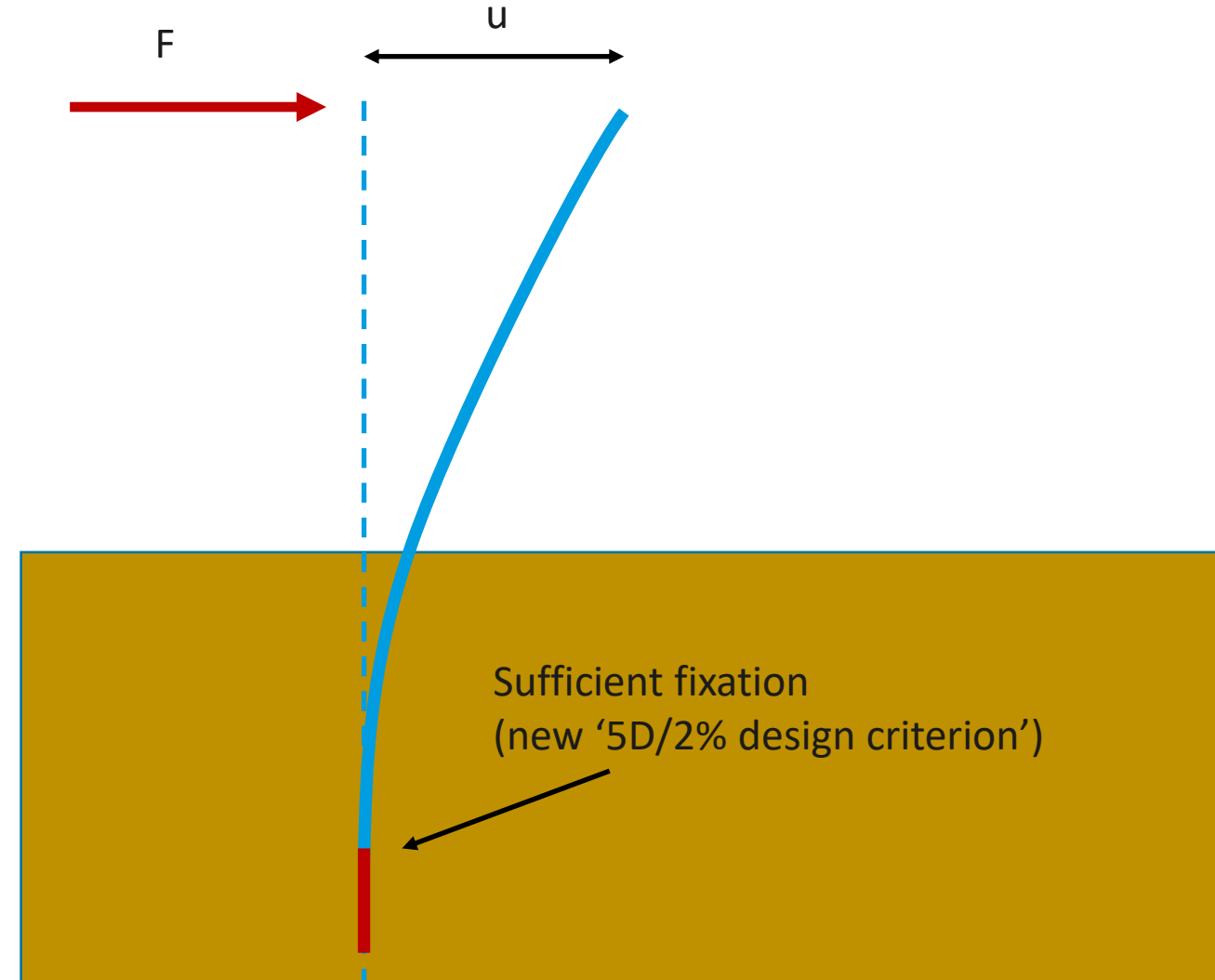


How to determine sufficient soil fixation?

- New method included in CROW 2017 design guideline : Displacement of the pile head should be lower than 2% compared to an infinite long pile, which is modelled as a 5D longer pile.

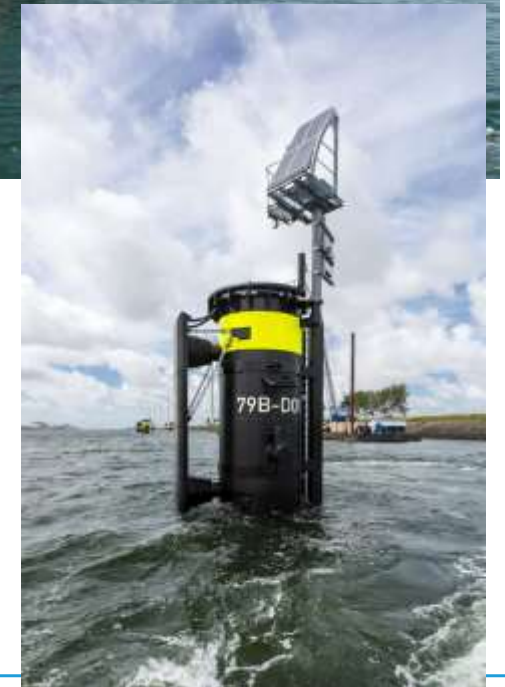
This criterion resulted in big discussions:

- Why 2% and not 5%?
- Consequence 10m longer piles
- In Rotterdam generally 2 - 6m longer piles.



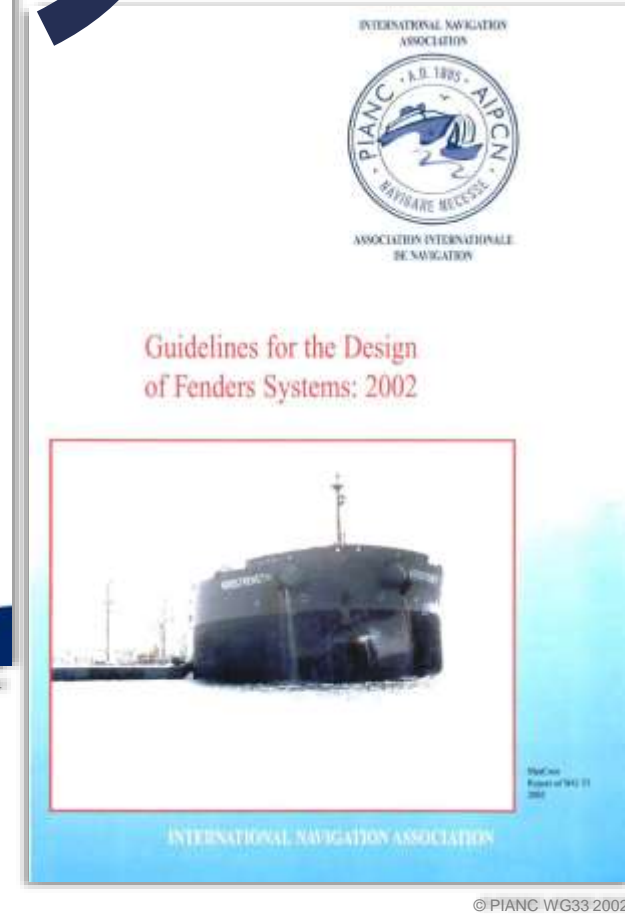
Revised CROW Flexible Dolphins in 2024

- Berthing energy and mooring loads
- Fixation and repetitive loads
- Local buckling
- Design approach
- Lessons learned (beyond scope of this presentation)



Berthing energy & mooring loads

- New guideline for fender design (PIANC WG211, 2024)



CROW 2017 (PIANC WG33): Global safety factor	CROW 2024 (PIANC WG211): Load and resistance factor
<p>Determine normal energy</p> $E_d = \frac{1}{2} M V_B^2 C_e C_m C_s C_c$ <p>Determine abnormal energy</p> $E_{ab} = C_{ab} E_d$ <p>Capacity of selected fender</p> $E_f = \frac{E_{RPD}}{F_{TOL} F_{ANG} F_{TEM} F_{VEL}}$ <p>Limit state verification selected fender</p> $E_f \geq E_{ab}$	<p>Determine characteristic energy</p> $E_{k,c} = \frac{1}{2} M_c V_{B,c}^2 C_{e,c} C_{m,c}$ <p>Design energy: 8-step approach for γ_E</p> $E_{k,d} = \gamma_E E_{k,c}$ <p>Design capacity of selected fender</p> $E_{f,c} = E_{base} C_{ang,c} C_{t,c} C_{v,c} C_{mult,c}$ $C_{mult} = \frac{E_{f,system}}{E_{base}} = \frac{\sum_{i=1}^{n_f} E_{f,i}}{E_{base}}$ $E_{f,d} = \frac{E_{f,c}}{\gamma_m}$ <p>Limit state verification selected fender</p> $E_{f,d} \geq E_{k,d}$

Berthing velocity

- Reliability of berthing velocity dominates uncertainty in calculating berthing energy for 85% (Ueda et al., 2010)

$$E_{kin} = 1/2 M v^2 C_m C_s C_c C_E$$

in which:

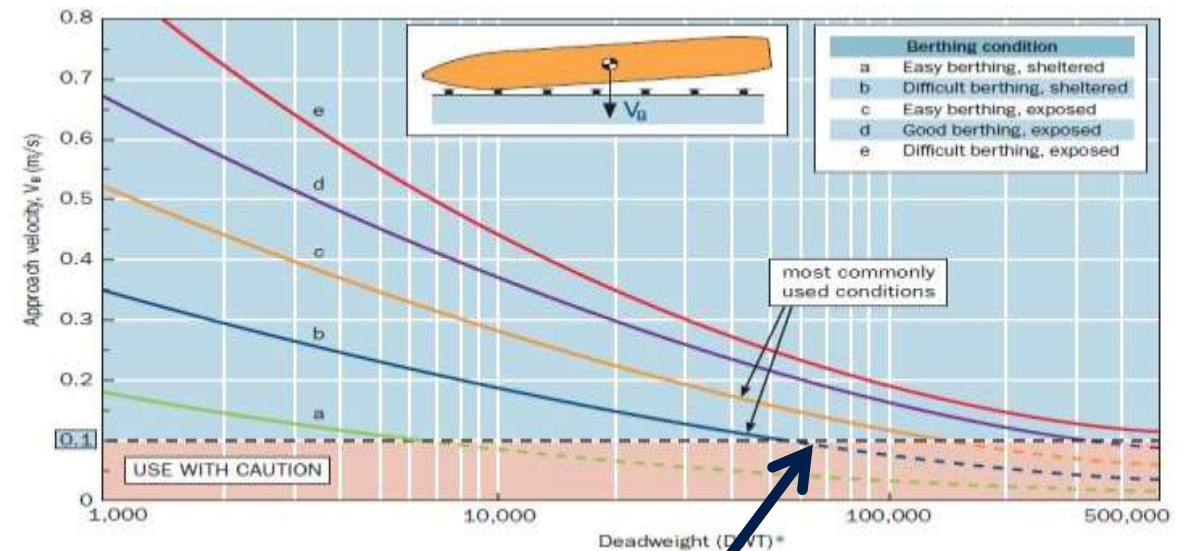
E_{kin}	Kinetic energy [kJm]
M	Mass of vessel/water displacement [tonnes]
v	Total translation velocity of centre of mass at time of first contact [m/s]
C_m	Virtual mass factor [-]
C_s	Ship flexibility factor [-]
C_c	Waterfront structure attenuation factor [-]
C_E	Eccentricity factor [-]

Berthing velocity

- PIANC 2002 (Guidelines for the Design of Fender Systems) is widely accepted in the industry.
- Berthing velocity curves and berthing angles are based on research conducted in 1972, (Brolsma et al, 1977)



Absorb ship's berthing energy and
reduce berthing impact force



Strong negative correlation

Data collection PIANC WG145

Methods used to collect data:

- Interviews/questionnaires
- Laser docking aid systems
- Portable Pilot Units (PPU)
- Smart dock portable workstation

Vessel Type	Number of ports	Number of collected data	Number of data for vessels > 30,000 DWT
Bulk	2	243	243
Container	8	1644	1068
LNG	1	70	70
Oil tanker	3	486	472
Total	14	2443	1853



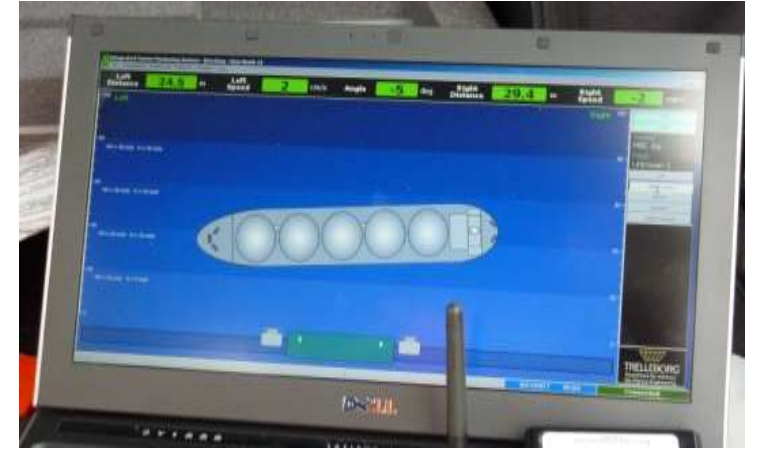
Measurements Maasvlakte Rotterdam



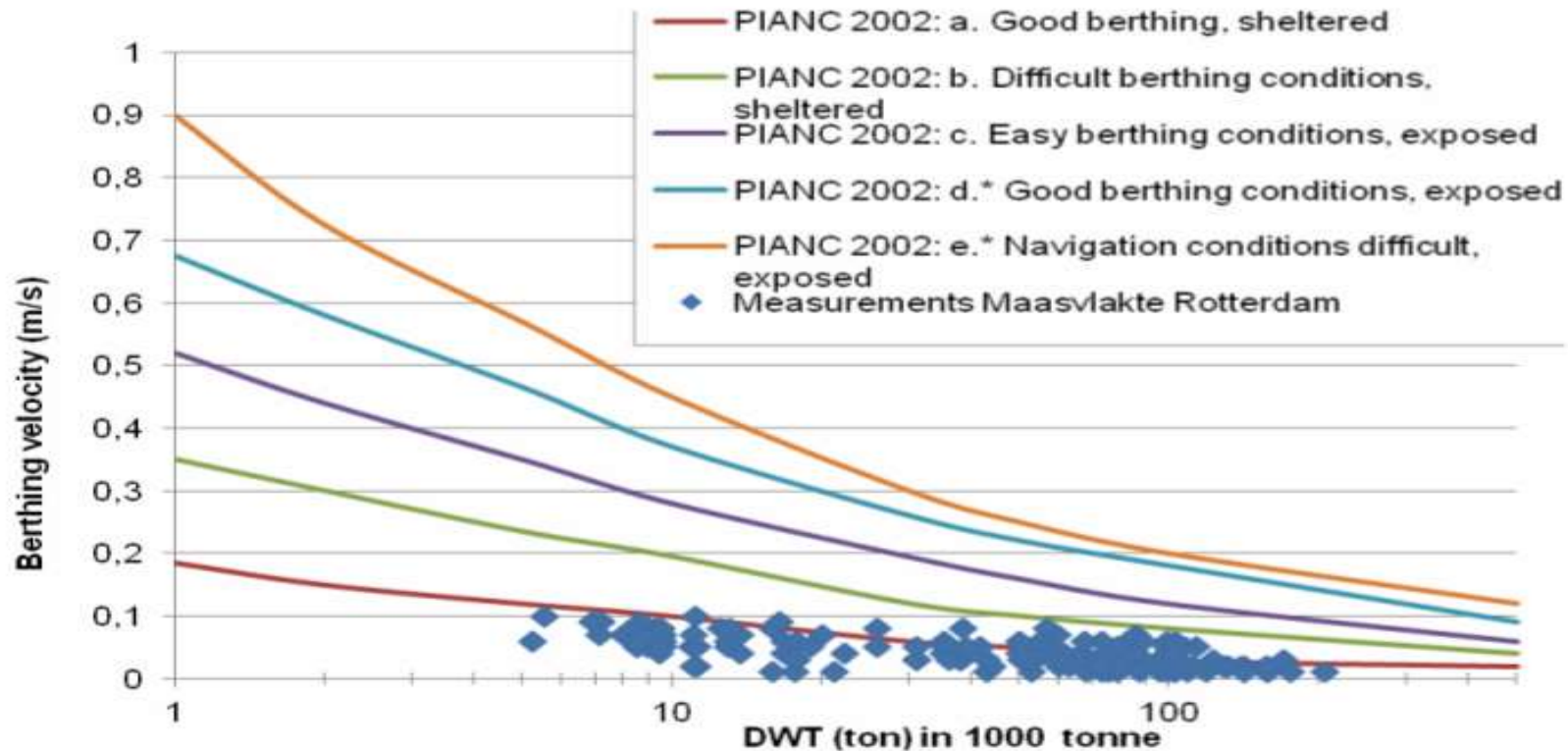
— Container berths

— Tanker berths

— Bulkher berths

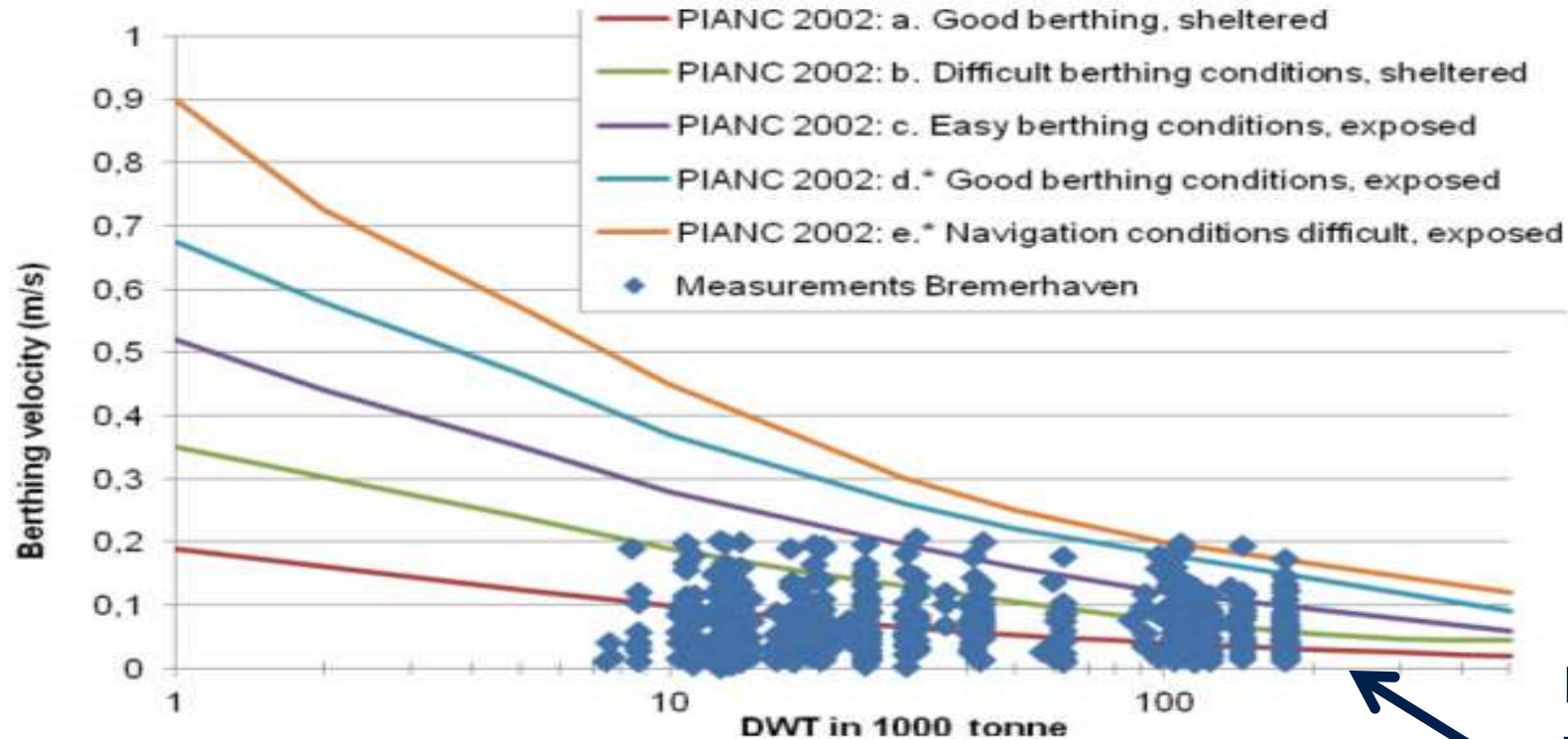


Measurements Rotterdam (Container vessels)



- Sheltered conditions
- Parallel landing
- Mean 3-4 cm/s
- Max 10 cm/s
- Low berthing angle
- 3 months of data

Measurements Bremerhaven (Container vessels)



- High tidal current
- Angular landing
- Mean 5-6 cm/s
- Max 20 cm/s (2013)
- Max 26 cm/s (2018)
- Very low berthing angle
- 8 years of data

Large variation in berthing velocity

Recommendations in PIANC WG211 for velocities [cm/s]

- PIANC WG211 recommends to use site-specific information e.g.
 - a) berthing records/field observations,
 - b) insights from pilots/masters,
 - c) global company records,
 - d) speed limits,
 - e) operational limits,
 - f) past service performance.



Recommendations in PIANC WG211 for velocities [cm/s]

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- f) past service performance.

Navigation Condition:	Favourable	Moderate	Unfavourable
Type of Vessel ^a	$V_{B,c}$ (m/s)		
Coaster	0.180 ^b	0.300 ^a	0.400 ^a
Feeder, Handysize	0.150 ^b	0.225 ^c	0.300 ^d
Handymax, Panamax	0.120 ^b	0.200 ^{a,d}	0.275 ^d
Vehicle Carriers	0.120 ^a	0.200 ^a	0.275 ^a
Post Panamax, Capesize (small), Aframax	0.100 ^{b,e}	0.175 ^c	0.275 ^d
New Panamax, Capesize (large), Suezmax, ULCV, VLBC, VLCC, ULCC	0.100 ^{b,e}	0.150 ^{c,f}	0.250 ^d
Cruise & Passenger Vessels	0.100 ^a	0.150 ^{a,f}	0.250 ^a

a. Typical vessel dimensions: Coaster (5,000-15,000 DWT), Feeder, Handysize (15,000-42,000 DWT), Panamax, Handymax (42,000-85,000 DWT), Post Panamax, Capesize, Aframax (85,000-115,000 DWT), New Panamax, Capesize, Suezmax (115,000-170,000 DWT), ULCV, VLBC, VLCC, ULCC (>170,000 DWT). For vessels not listed in the table (e.g. LNG) use equivalent size. Although most gas tanker owners have their own global data set.

b. These recommended berthing velocities are largely based on field measurements in Rotterdam and Wilhelmshaven, (PIANC WG145, 2022), (Roubos, Gaal, Hein, Iversen, & Williams, 2022).

c. These recommended berthing velocities are largely based on the normal navigation conditions distinguished by PIANC WG 145 (PIANC WG145, 2022) and verified by WG 211 against new data sets from Poland, Korea, US and India.

d. These recommended berthing velocities are largely based on the measurements conducted in Bremerhaven, (PIANC WG145, 2022), (Roubos, Gaal, Hein, Iversen, & Williams, 2022).

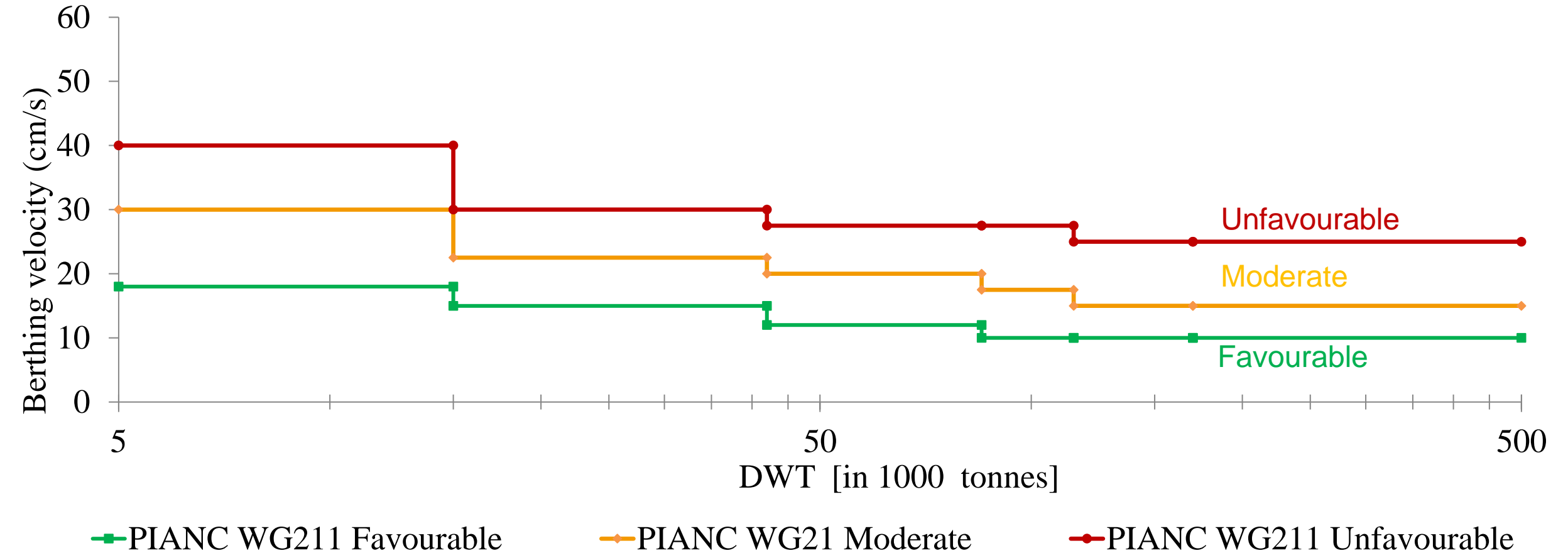
e. These recommended berthing velocities are based on interviews with masters, pilots, harbour masters and experienced port engineers. The values are based on comparison with similar vessel sizes.

f. These recommended berthing velocities are based on EAU 2012 and RDM 2.0-11 (2012).

g. Some unpublished berthing records, of berths claiming to be moderate, include slightly higher velocities. BS6349 and WG 211 consider this value to be sufficient for the majority of berths.

- In the absence of site-specific information Table 5.3** of PIANC WG211 provides recommendations for characteristic berthing velocity.

Visualisation Table 5-3 PIANC WG211



Dirk-Jan Jaspers Focks (Witteveen+Bos)

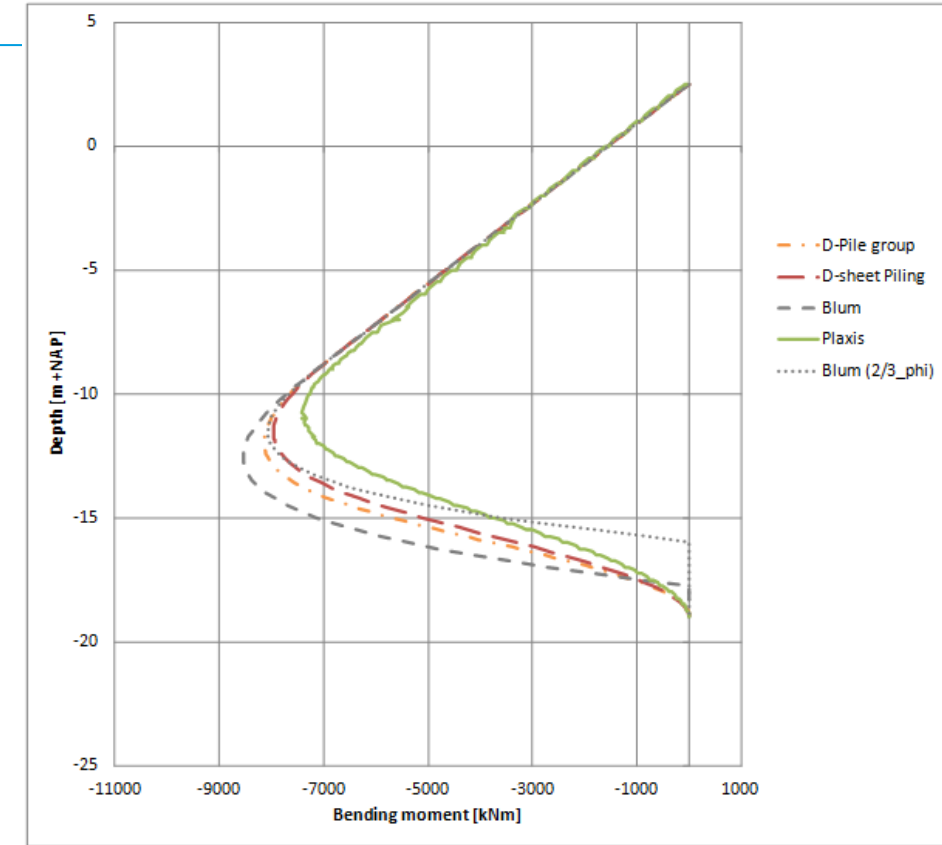
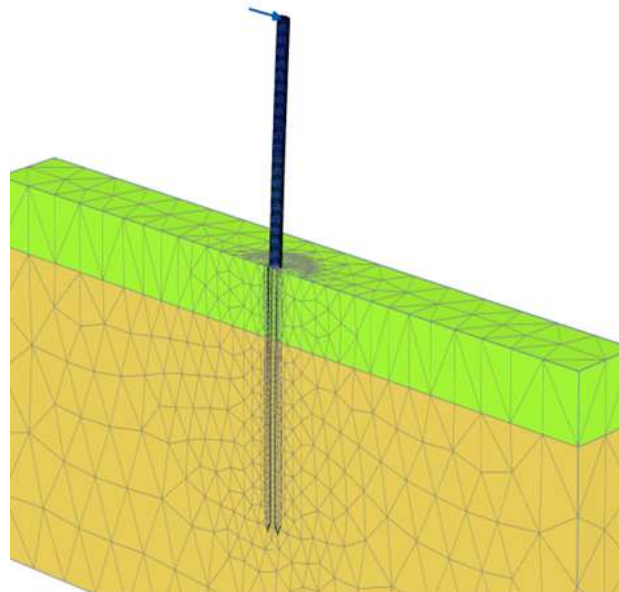
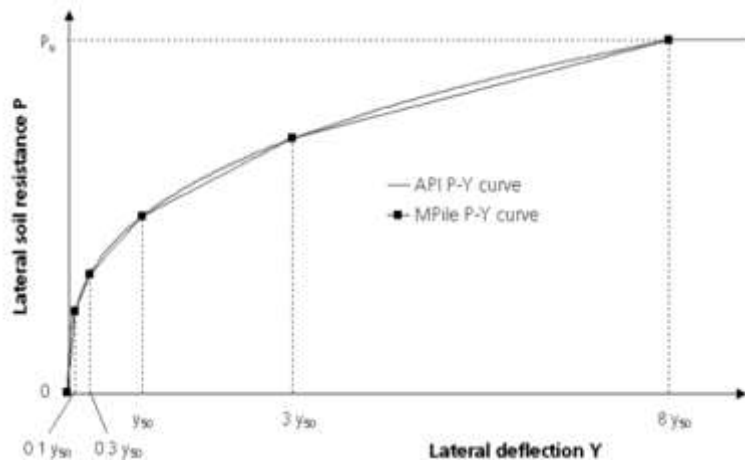


- Geotechnical Engineer (18 years) at Witteveen+Bos
- Involved in >100 designs of maritime structures
- Lecturer PAO (2010-present)
- Co-author of CUR/CROW publications: Handbook Quay Walls, Hydraulic Fill manual, Flexible Dolphins
- Member of several national committees (NEN, CUR and CROW)

Modelling tools dolphins

Various models available:

- Force-equilibrium
- Elasto-plastic spring-models
- Finite Element Method (FEM)
with significant differences in outcome



Pile tests Beneluxhaven

Innovative combination of software and measurements systems

SAAF
(inclinometers)

Local
buckling

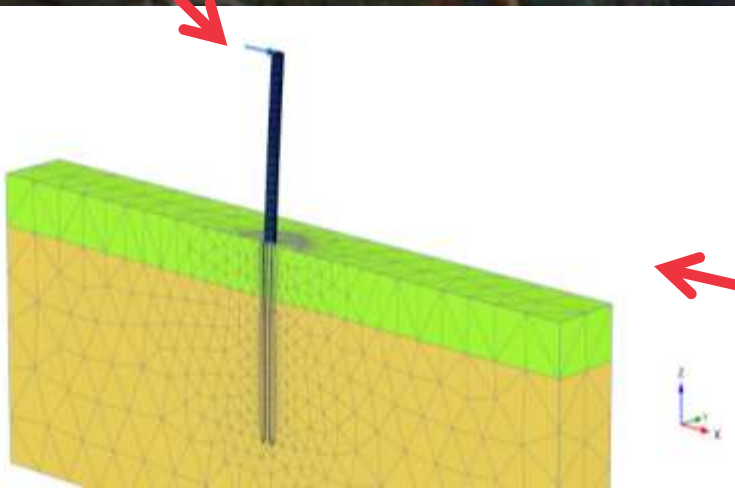
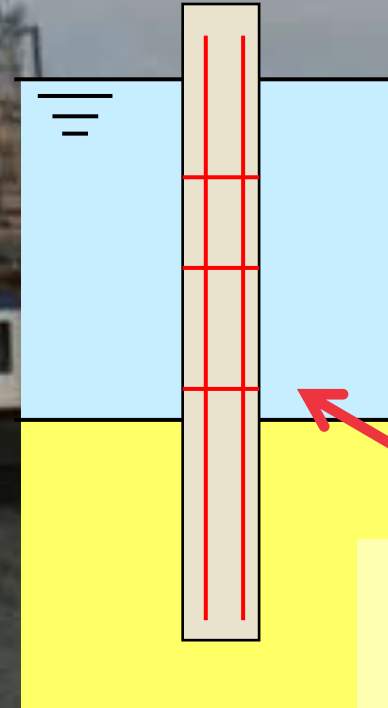
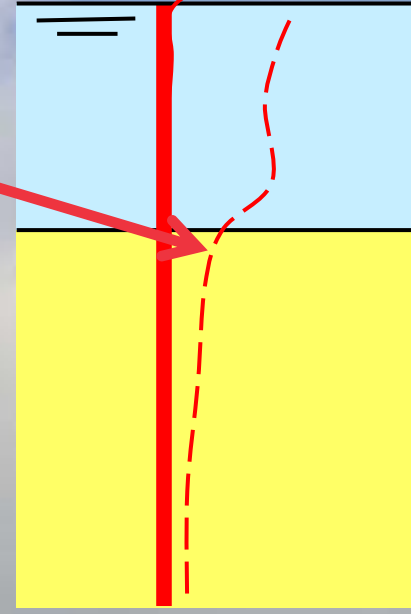
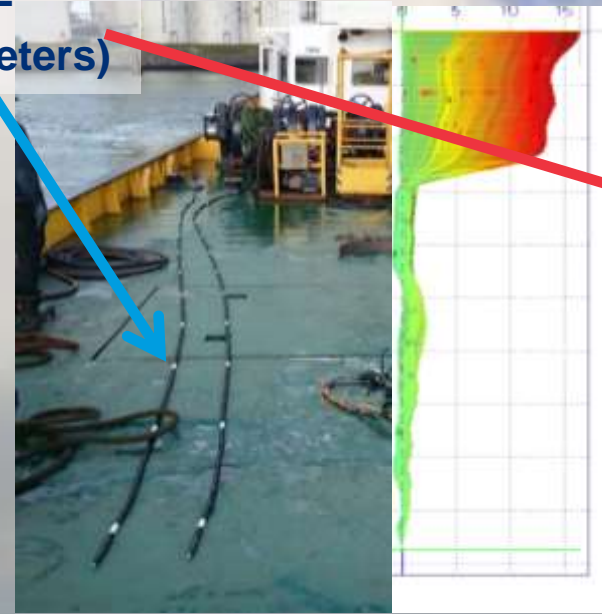
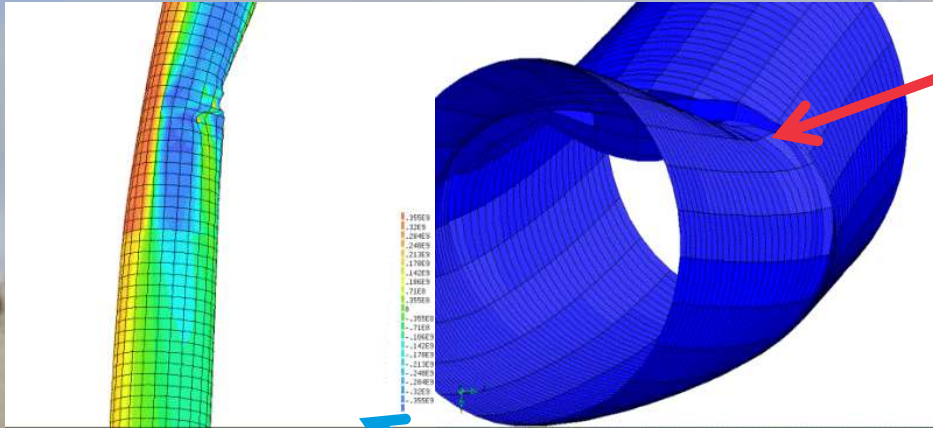
DIANA

Berthing load

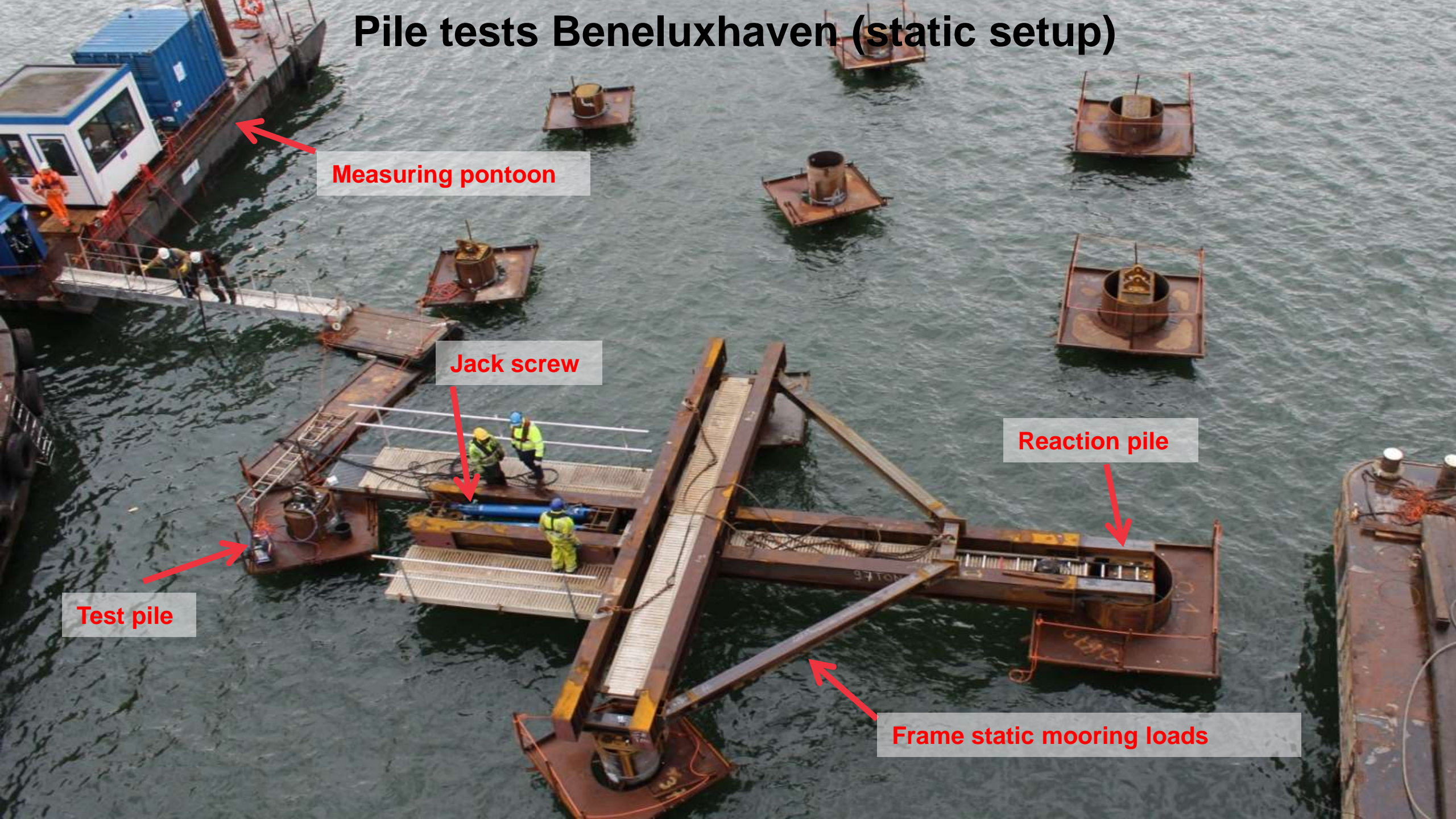
Benchmarks:

- Plaxis 3D
- Dsheet
- Blum

Fibre optic
strain sensors
0,25mm



Pile tests Beneluxhaven (static setup)



Measuring pontoon

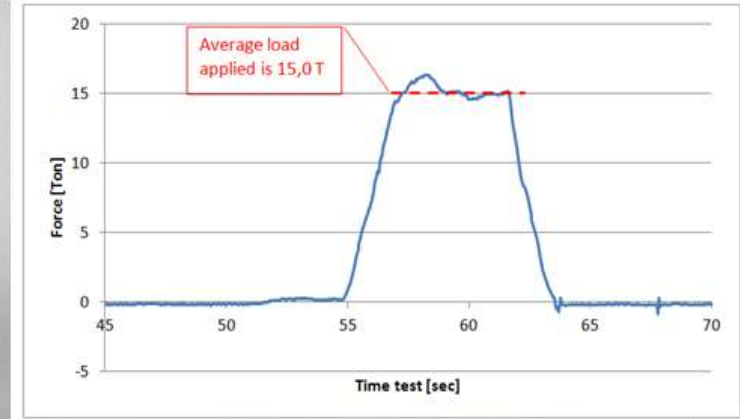
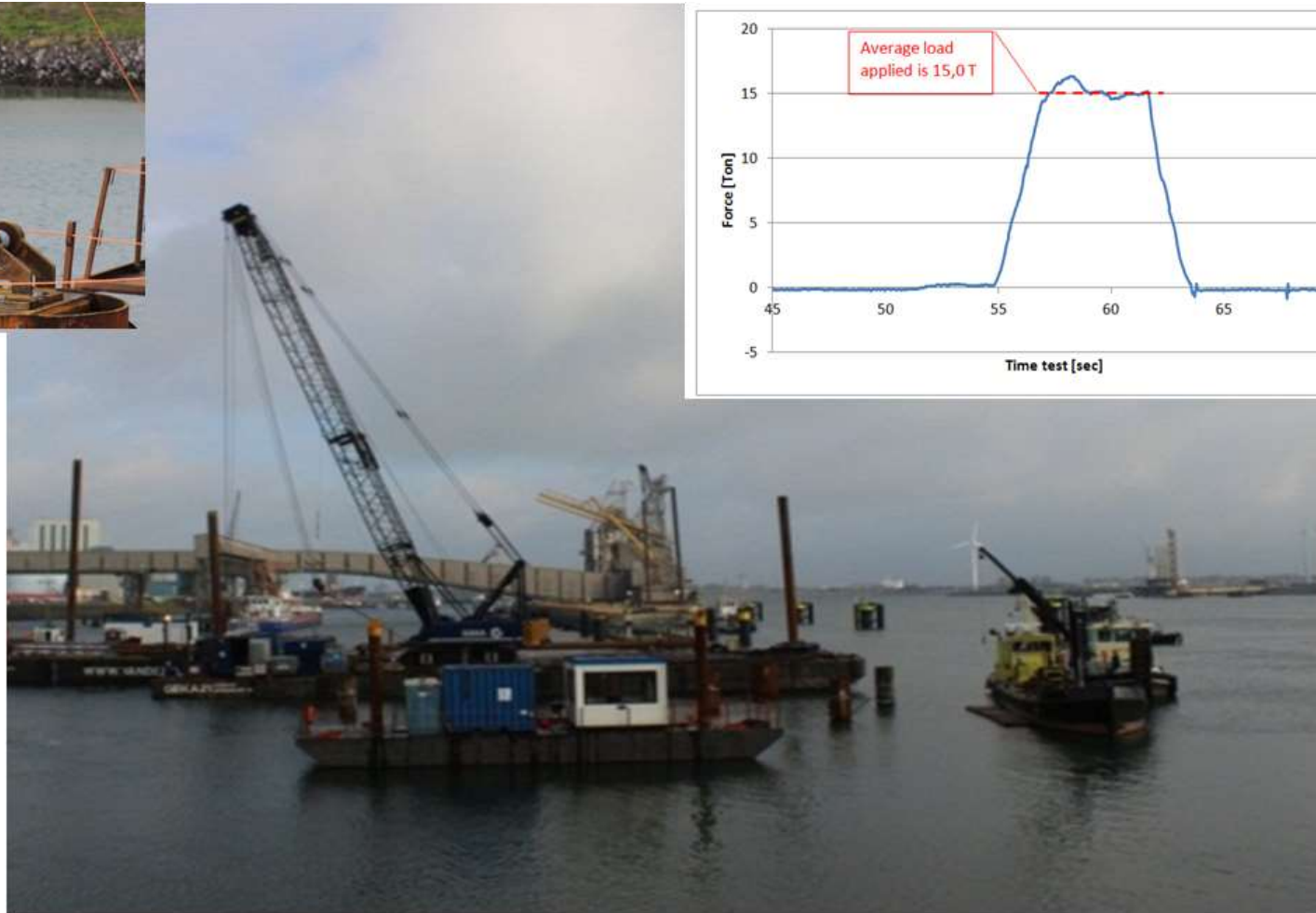
Jack screw

Reaction pile

Test pile

Frame static mooring loads

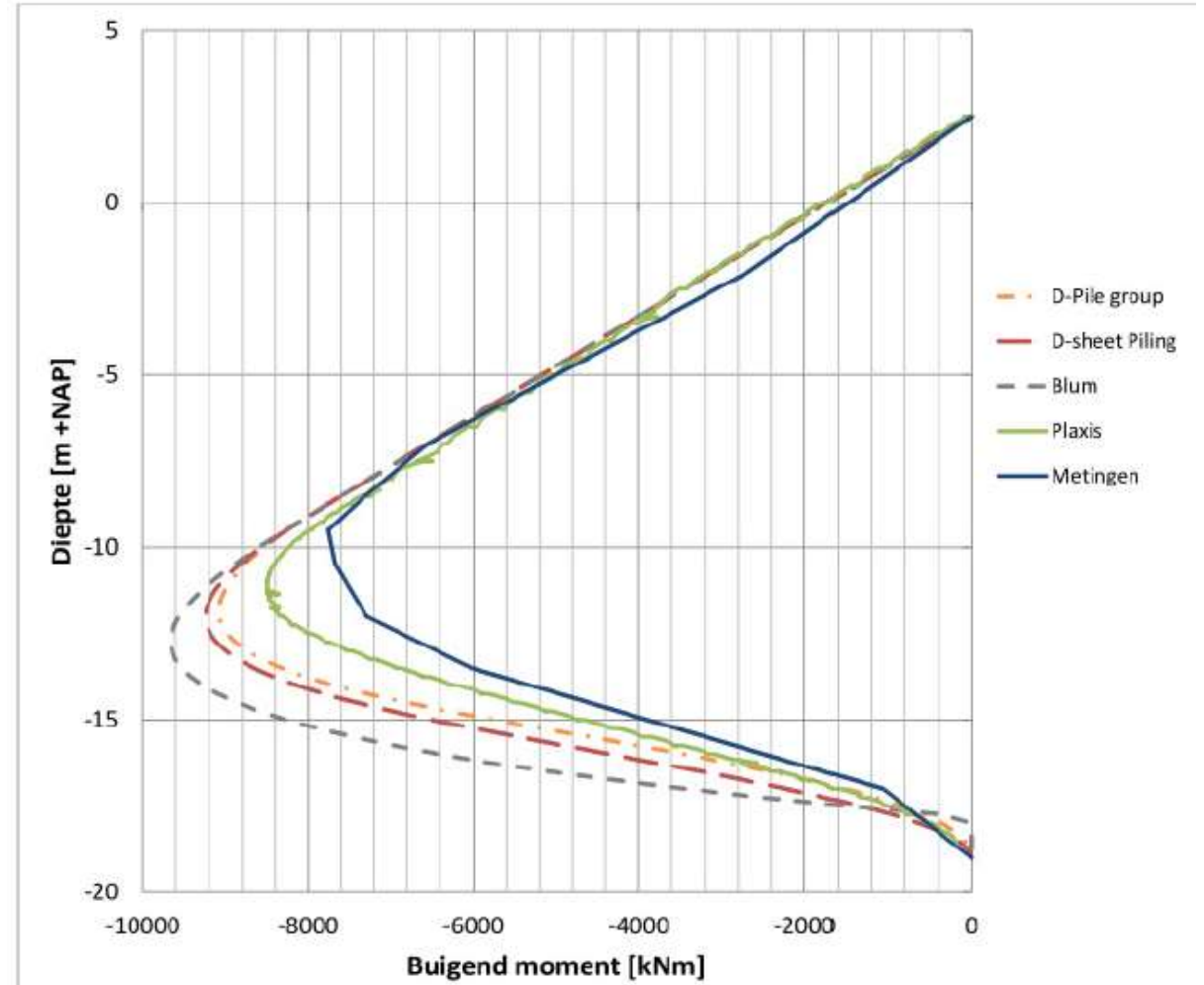
Pile tests Beneluxhaven (“dynamic” setup)



Pile tests Beneluxhaven: Results

Main takeaways:

- Significant differences in results
- Advanced models provided best results
- Most models are allowed, but some specific exceptions

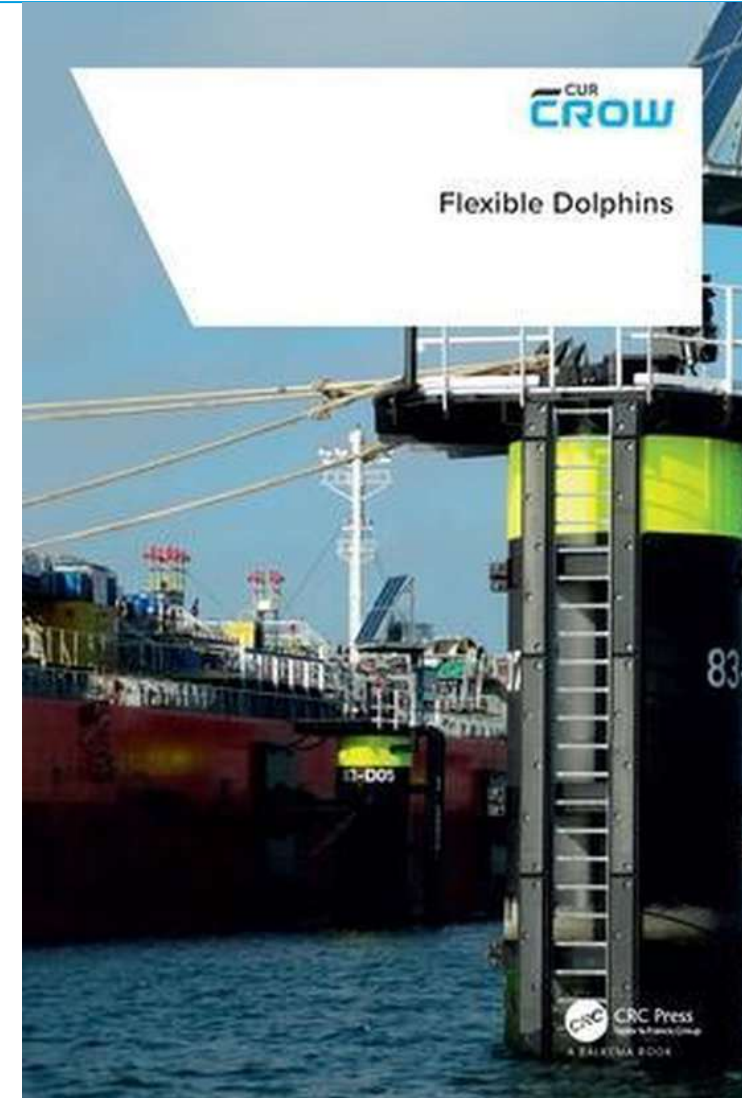


Tests in Beneluxhaven

Beneluxhaven (2015) tests formed the basis of:

- Selection on applicable design models
- Their limitations and advantages
- Local buckling criteria

Included in first edition Handbook Flexible Dolphins

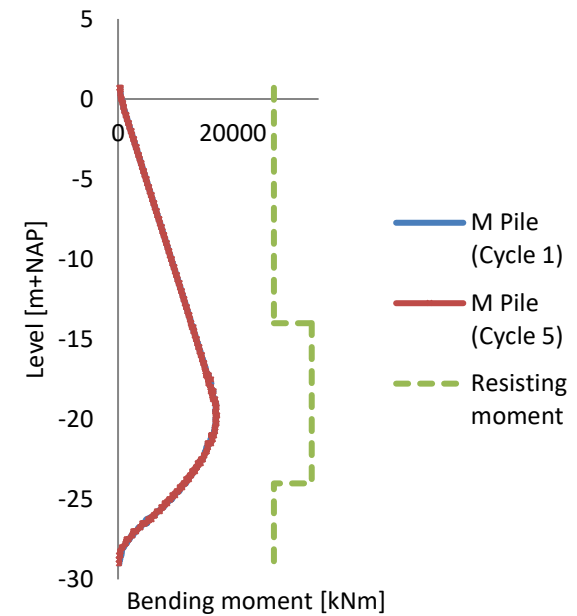
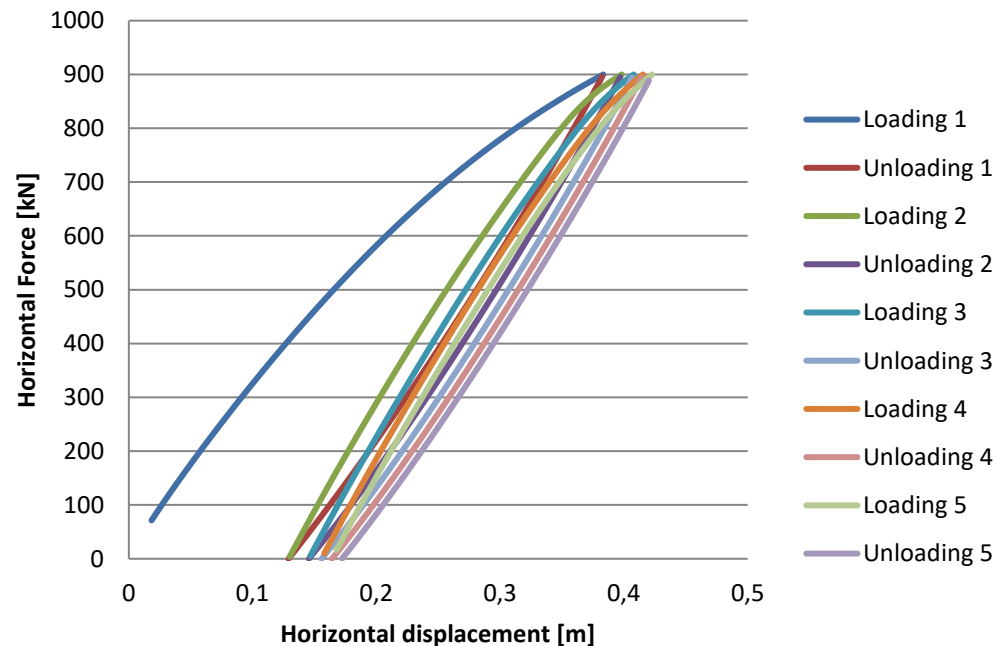


Tests in Beneluxhaven

But in Beneluxhaven:

- Repetitive loading was not tested
- Pile fixity (in relation to pile length) was not tested

Benchmarks in CROW showed effect of repetitive loading



Full scale tests Calandkanaal



Witteveen + Bos

Port of Rotterdam

deKlerk
WERKENDAM

deBoer

Civiele technieken deBoer bv

Iv-Infra

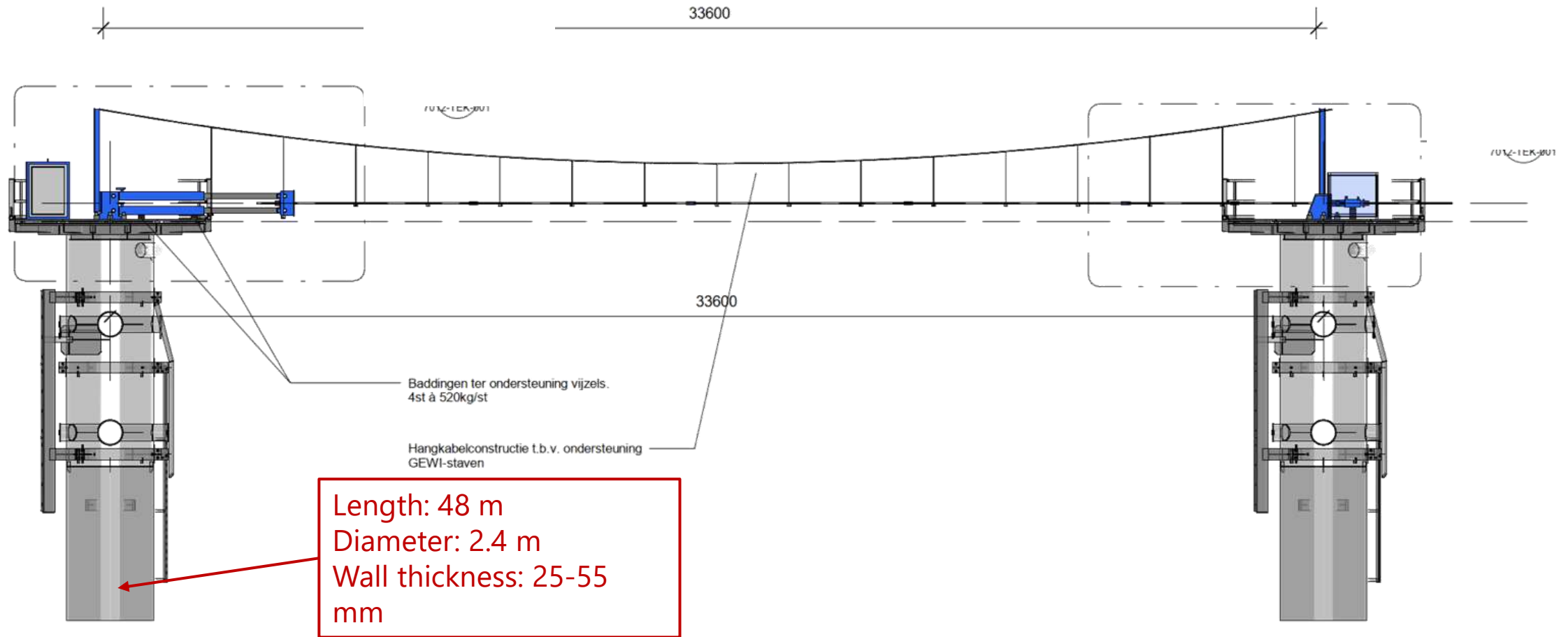
Gemeente Rotterdam

Witteveen + Bos

Port of Rotterdam

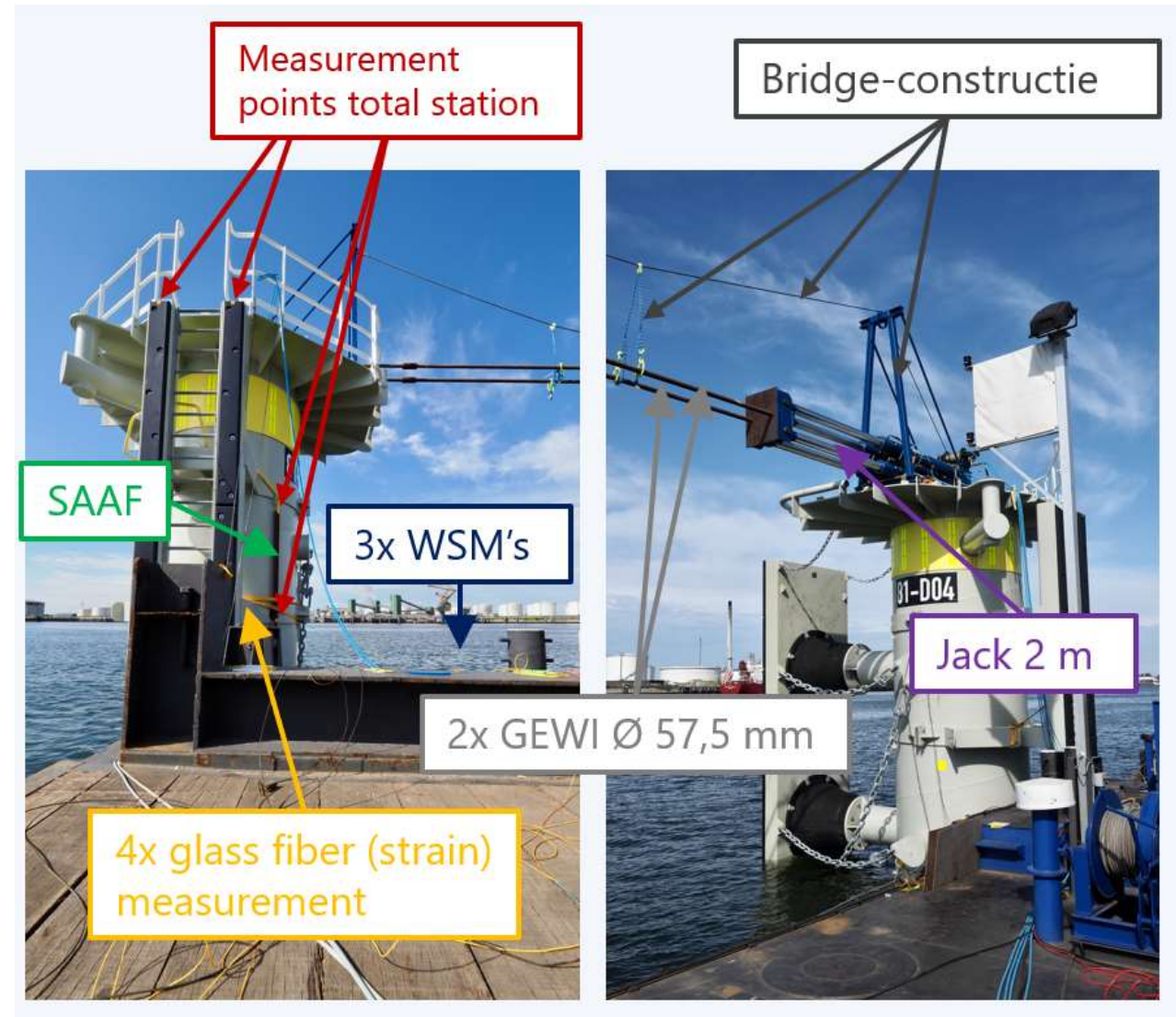
kennisplatform
CROW

Full scale tests Calandkanaal



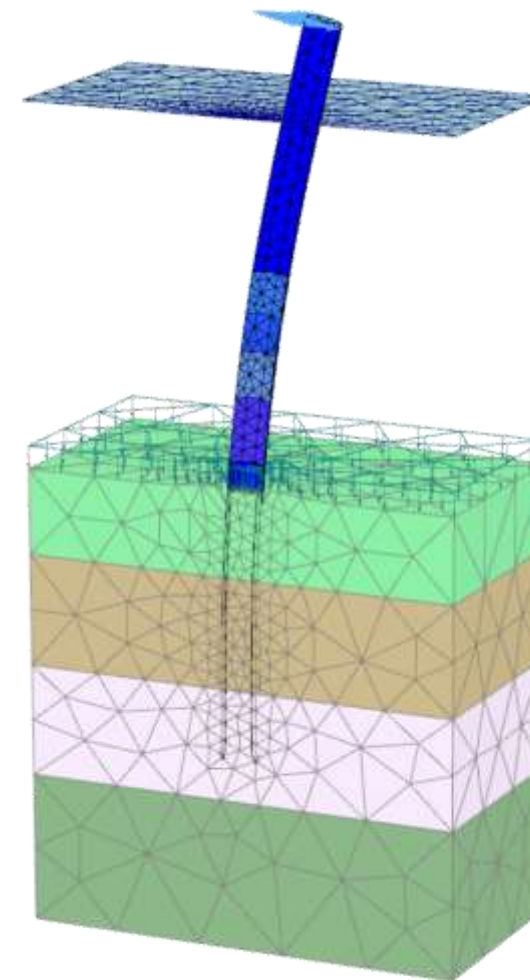
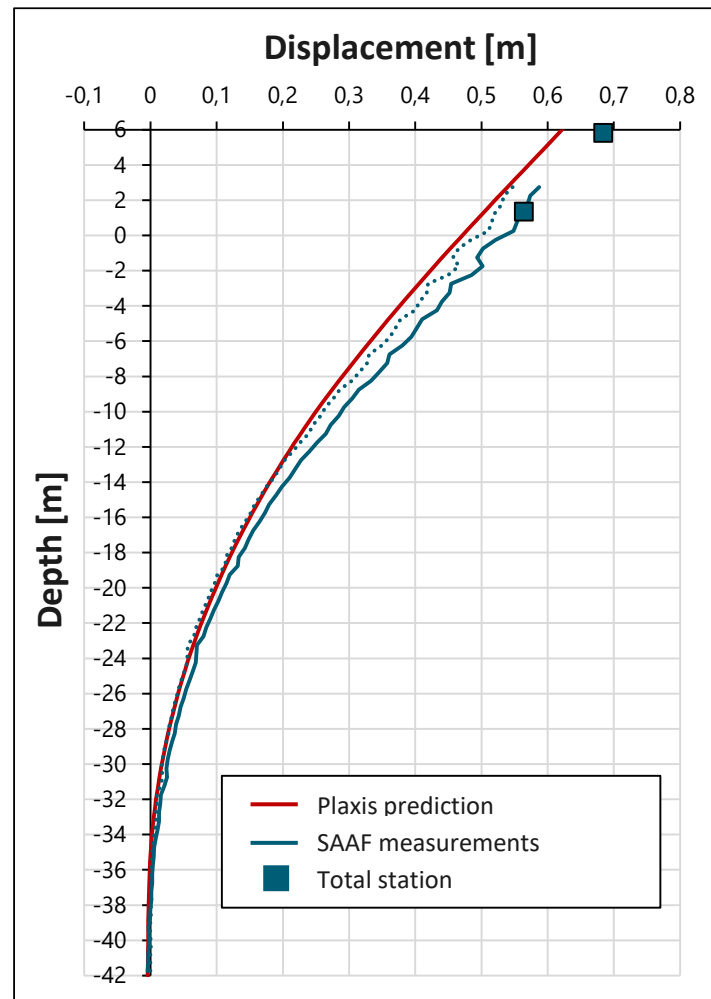
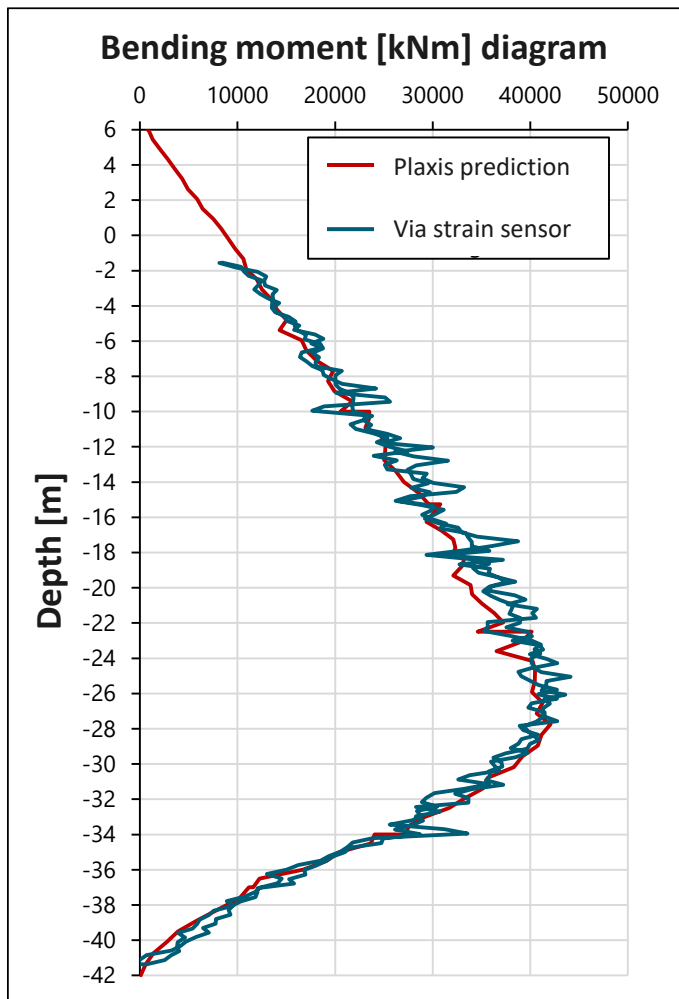
Full scale tests Calandkanaal

- Test load ≈ 1820 kN (90% of ULS load)
- Max deformation ≈ 1 m.
- Sensors:
 - BOFDA fibre optics
 - SAAF
 - water pressure sensors
 - total station



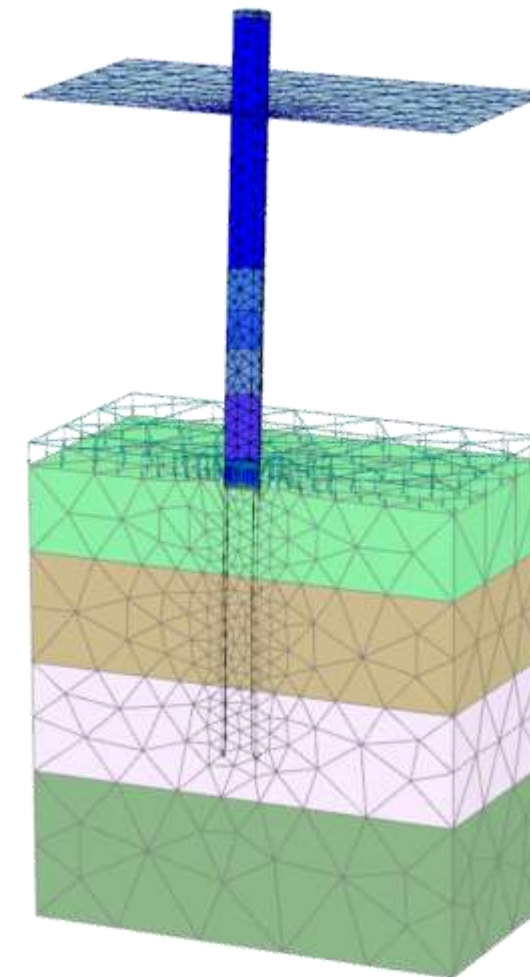
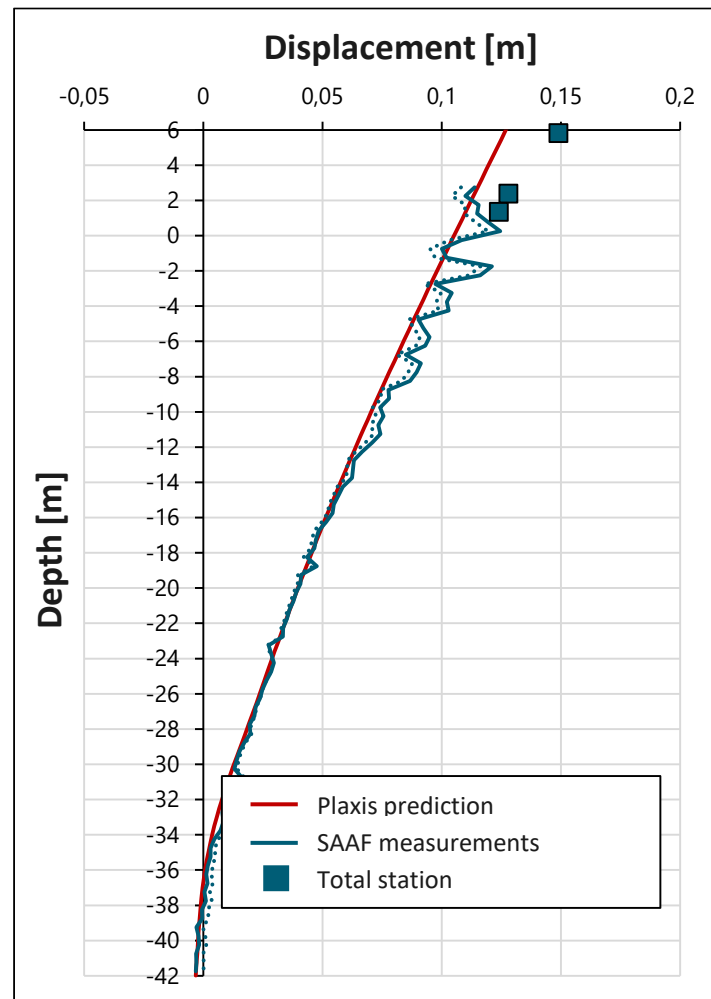
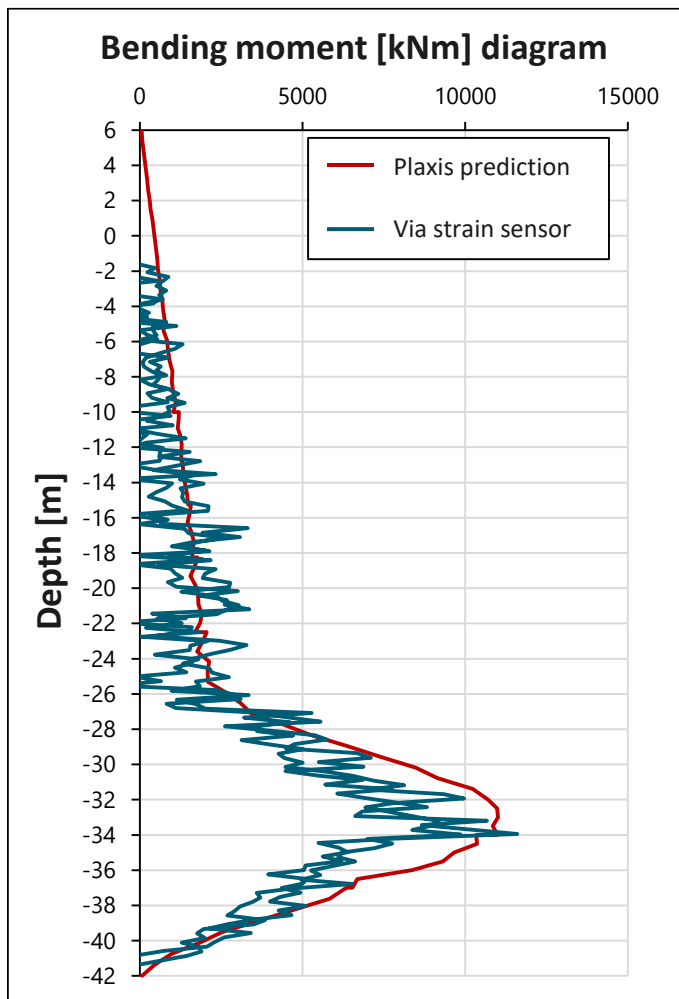
Full scale tests Calandkanaal: results

Repetitive loading : loading step 1



Full scale tests Calandkanaal: results

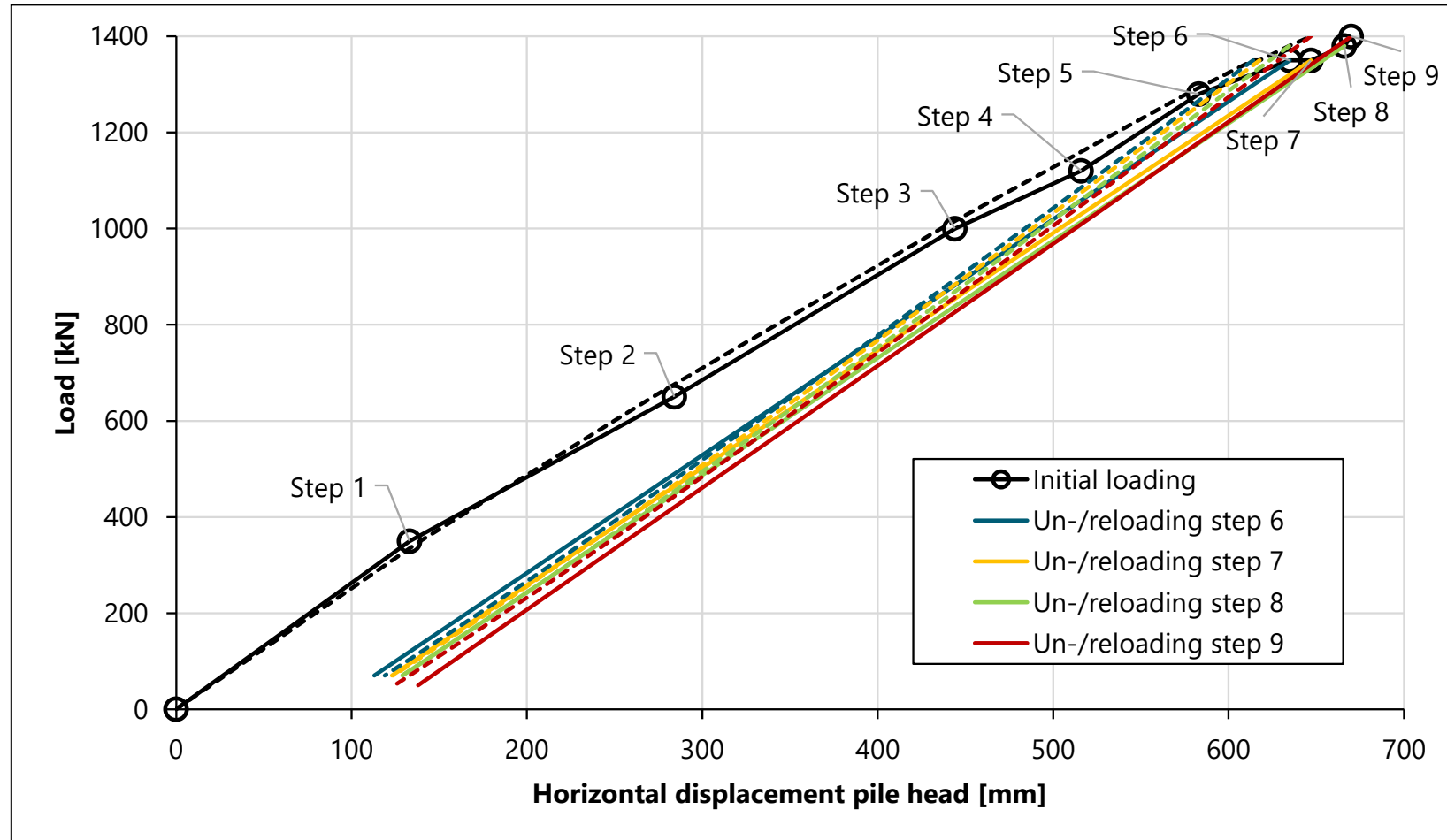
Repetitive loading : unloading



Full scale tests Calandkanaal: results

Repetitive loading : reloading

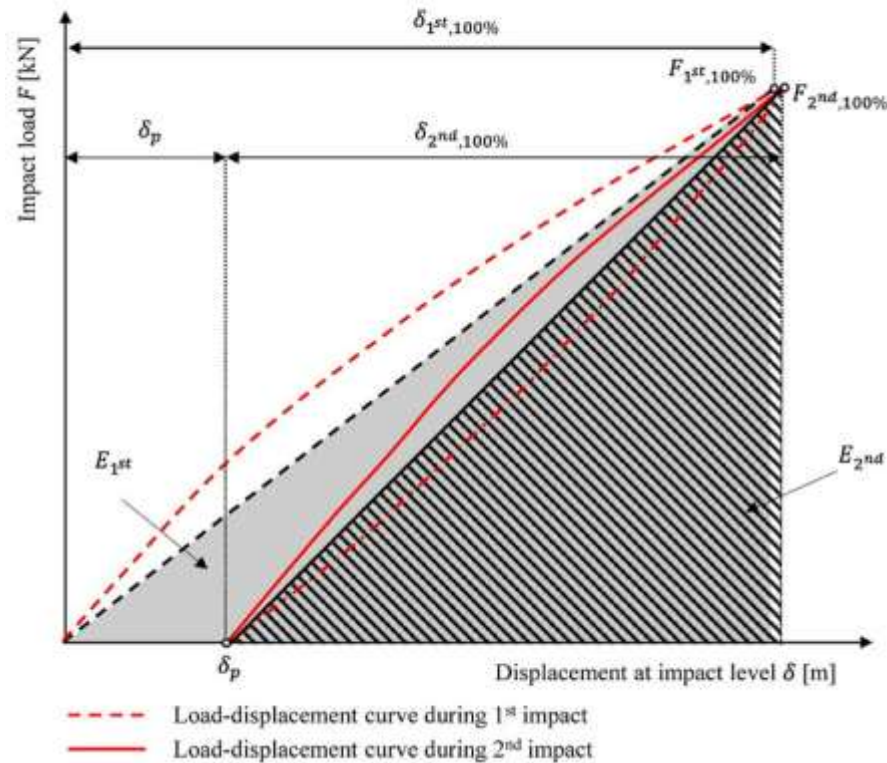
- Continuous: measurements
- Dashed: model (Plaxis 3D)



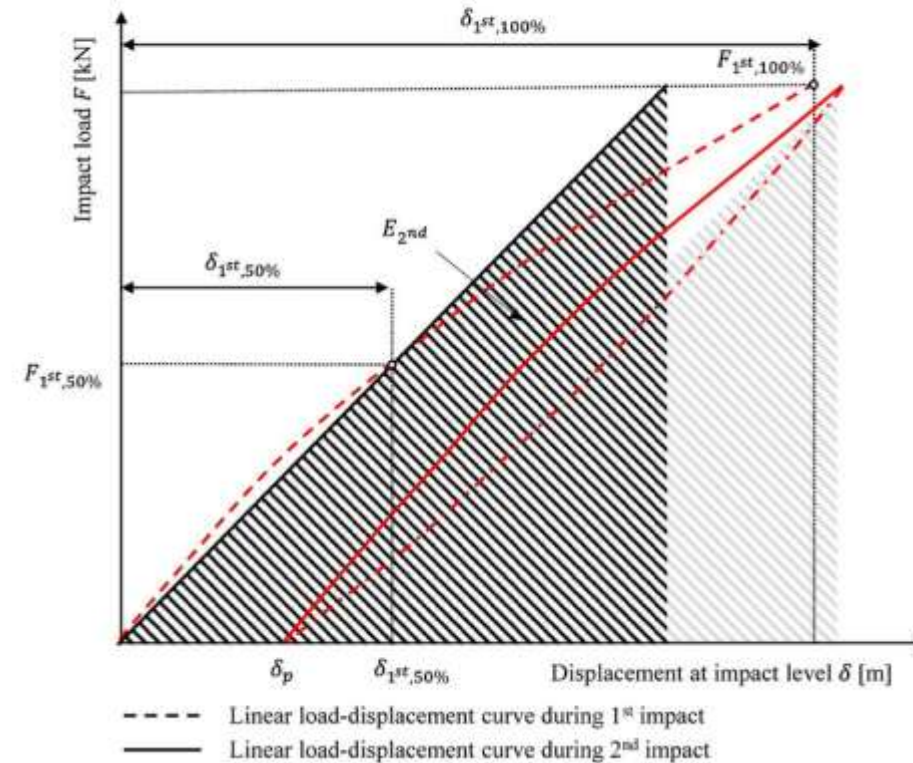
New design approach

- Repetitive loading behaviour needs to be included: use 2nd berthing impact in design

A) Linearization load-displacement curves during 1st and 2nd impact



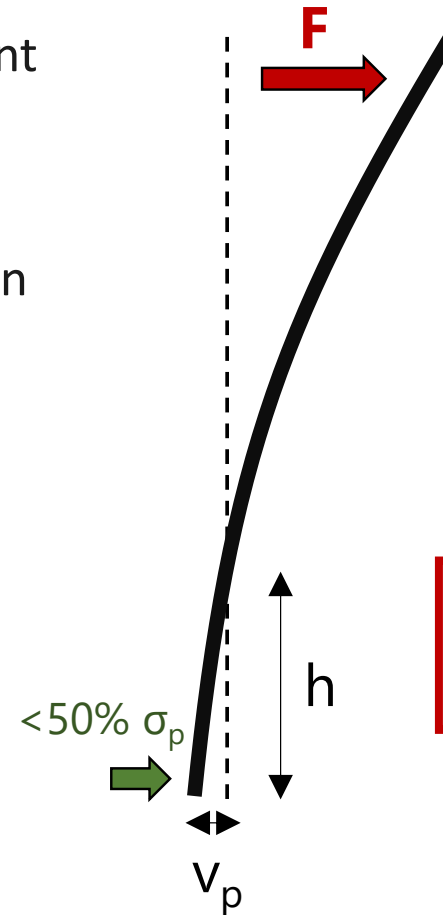
B) Transformation load-displacement curve of the 2nd impact



New design approach

Fixity criteria in first edition is too conservative

- New guidelines for soil fixation for different design methods (e.g. Blum, p-y cures and finite element models such as Plaxis)
- ULS geotechnical failure 100% mobilisation of passive soil wedge (ULS energy once in the service life)
- SLS fixity check: 50% mobilisation of passive soil wedge after 2nd berthing impact. Except:
 - Blum-method 33% mobilisation
 - 3D FEM: 50% or v_p/h criterion NEN 9997-1 appendix C.3

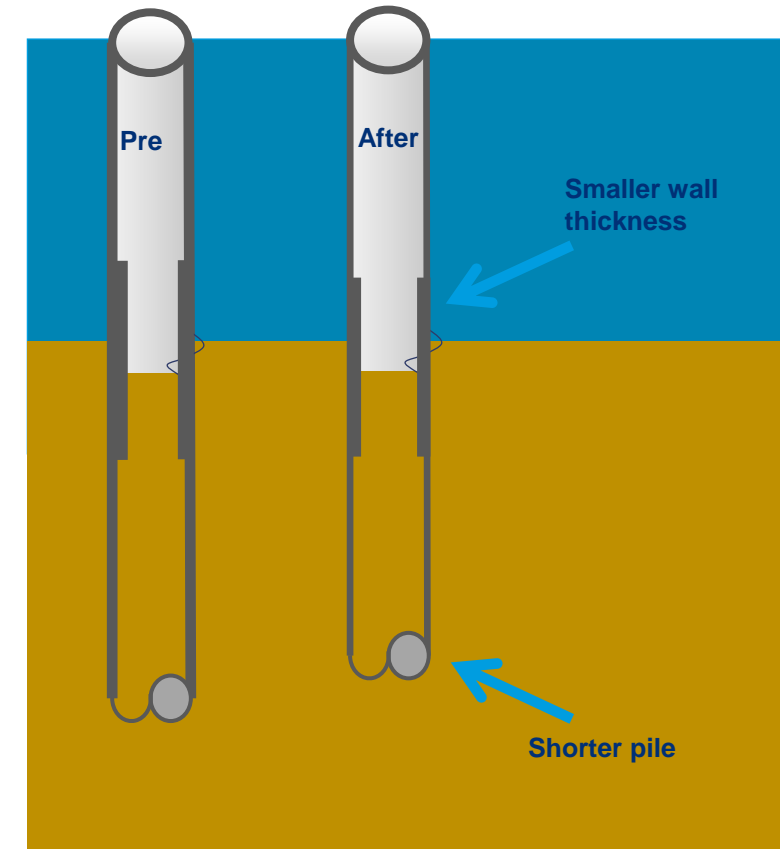


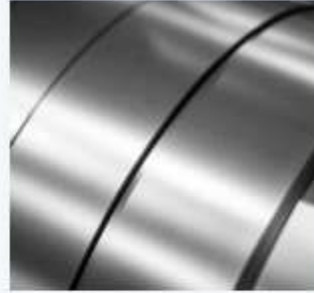
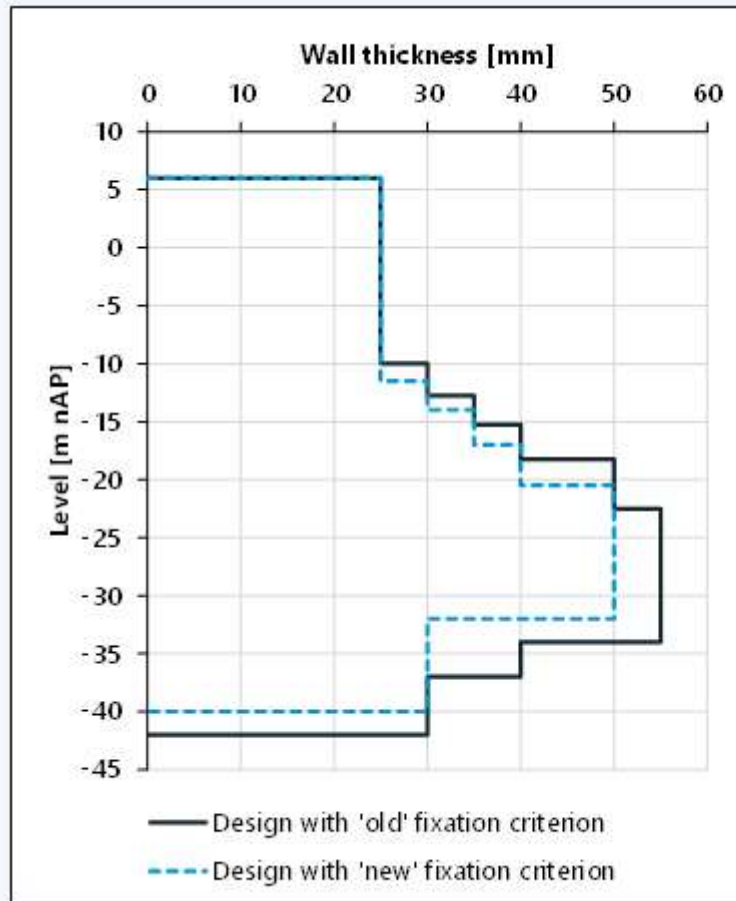
Tabel C.2 — Verhouding v_p / h en v / h voor $0,5\sigma_p$ voor niet-cohesieve grond

Soort wandbeweging	v_p / h (v / h voor $0,5\sigma_p$)	
	%	
	los gepakte grond	vast gepakte grond
a)	7 (1,5) tot 25 (4,0)	5 (1,1) tot 10 (2,0)
b)	5 (0,9) tot 10 (1,5)	3 (0,5) tot 6 (1,0)
c)	6 (1,0) tot 15 (1,5)	5 (0,5) tot 6 (1,3)

waarin:
 v is de wandverplaatsing;
 v_p is de wandverplaatsing om de passieve gronddruk te mobiliseren;
 h is de hoogte van de wand;
 σ_p is de volledig gemobiliseerde passieve grondweerstand.

- Uniformisation
- Less discussions expected on models
- Optimisation: Shorter dolphin piles and smaller wall-thicknesses.





13.4 ton/pile (-12.4 %)



21700 EUR/pile



14.7-29.5 ton CO₂/pile

Want more information?

- CROW Handbook Flexible Dolphins available on “kennisbank”
- PAO course “Dolphins & Jetties”

Publications: Beneluxhaven:

- Van der Meer, Jaspers Focks, Roubos
- ISSMGE en Vakblad Geotechniek Calandkanaal
- Sluis, Griffioen, Roubos
- ECSMGE en Vakblad Geotechniek



Evaluation full-scale mooring pile load test Rotterdam Évaluation de l'essai de chargement de poutre d'amarrage grandeur nature Rotterdam

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ABSTRACT: In the context of ERL, a full-scale pile test was carried out in the Caland Canal on behalf of the Port of Rotterdam authority. In this test, two large diameter mooring piles were pulled towards each other under lateral loading. The forces, displacements and strains were continuously monitored during V load-cycled steps. The aim of the test was to gain a better insight into the load-displacement behaviour of a mooring pile during repeated loading, and more specifically into the behaviour of the pile tip. The current design method proposed by the CROW publication Flexible Dolphins only results in mooring piles that are too long, due to the required fixation criterion in the publication. Witteveen+Bos performed the prediction and back analysis of the pile response with the use of the finite element method (FEM), the results of which are presented in this article. The results of the pile test highlight that the mooring pile may in fact be shorter with an alternative fixation criterion.

RESUME: Au cours de l'essai ERL, un essai de chargement grandeur nature a été réalisé dans le Canal Caland pour le compte de l'Autorité portuaire de Rotterdam. Lors de cet essai, deux poutres d'amarrage de grand diamètre ont été tirées l'une vers l'autre sous chargement latéral. Les forces, déplacements et déformations ont été continuellement mesurés pendant 9 étapes d'essai de chargement cycliques. L'objectif de cet essai grandeur nature est de mieux comprendre le comportement des poutres d'amarrage en déplacement latéral (en plus particulièrement la réaction de la pointe de la poutre). La méthode de conception actuellement proposée dans la publication ECSMGE Flexible Dolphins conduit à des piles trop longues, en raison du critère de fixation exigé dans la publication. Witteveen+Bos a réalisé la prédiction et la rétroanalyse de la réaction de la poutre avec la méthode des éléments finis (MEF), dont les résultats sont présentés dans cet article. Les résultats de l'essai de chargement ont permis d'établir que les poutres d'amarrage pourraient être plus courtes avec un critère de fixation alternatif.

Keywords: mooring pile, full-scale test, soil reaction, interaction, pile design

1. INTRODUCTION

In recent papers it has been noted that a number of design aspects included in the CROW publication Flexible Dolphins (CROW, 2016) could be improved. In particular, the degree of fixation of the mooring piles in the subsoil is a subject about which there is still a lot of uncertainty. The effect on the design outcomes can be significant.

The design method for determining the required pile length in CROW's Flexible Dolphins manual appears to be a conservative method, resulting in insufficient use of materials (piles that are too long). The behaviour of a mooring pile under repeated loading is also uncertain. Soil cracks will be

reopened, which means that in the event of a second and larger mooring thrust, the displacement is smaller, and therefore also the capacity to absorb the energy of a mooring ship through pile deflection.

2. PILE DESIGN AND TEST SETUP

2.1 Pile design

The mooring piles have a diameter of 2.4 metres and are made up of sections with different optional soil thicknesses, see Table 1.

The piles were characterised by energy absorption and mooring head load (or MAF -1.7 m), in addition,



Thank you for your attention!

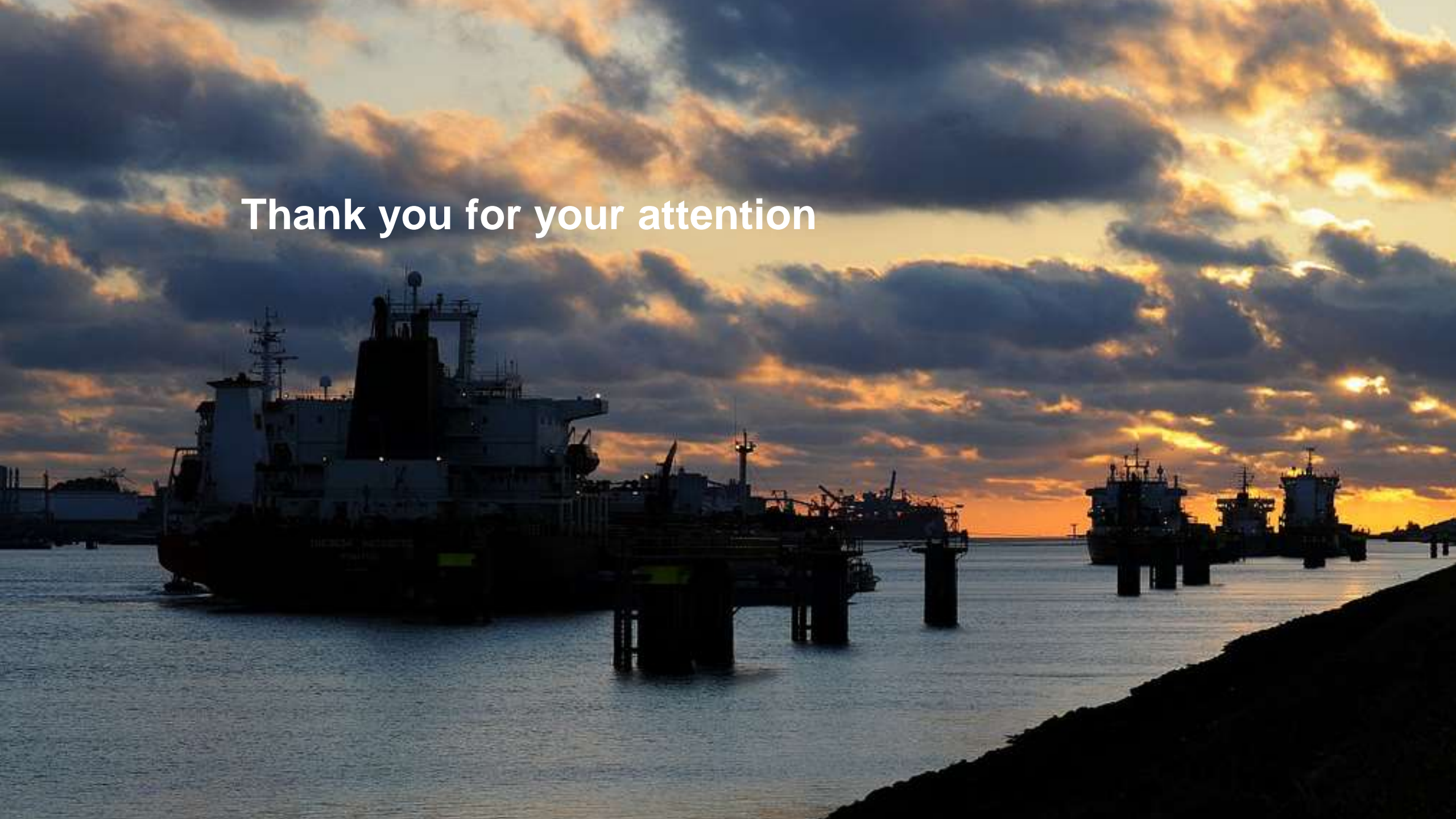
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Bedankt voor je aandacht



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Delphina

- Dolphin refers to delphina (Greek):
 - ⇒ Delph (hollow), delve (dig into the world)
 - ⇒ Dolphins are also installed deeply into the soil.
- Delphin (Latin) => Dalben (German) => Delven (NL)
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Less plausible

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