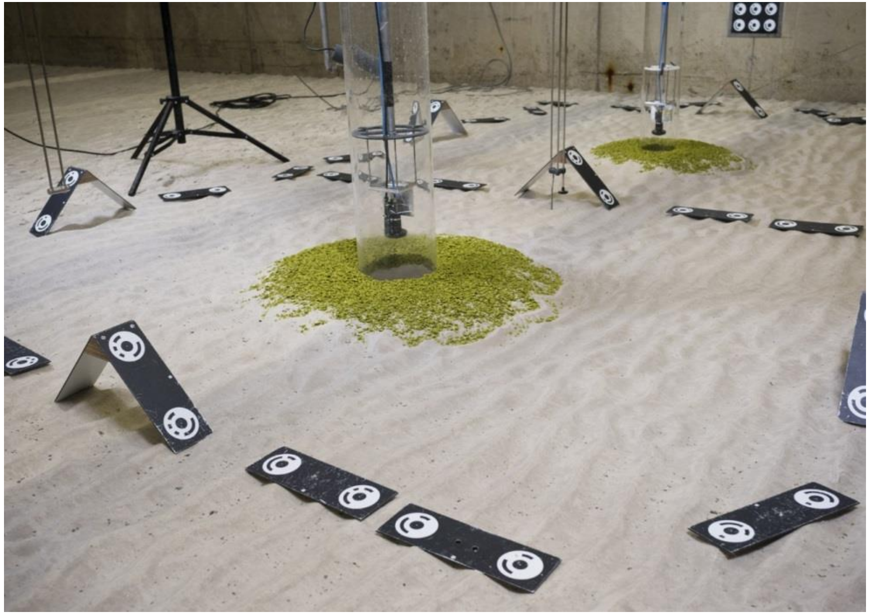
Netherlands Enterprise Agency

Webinar Scour & Scour Mitigation for Hollandse Kust (zuid) WFZ

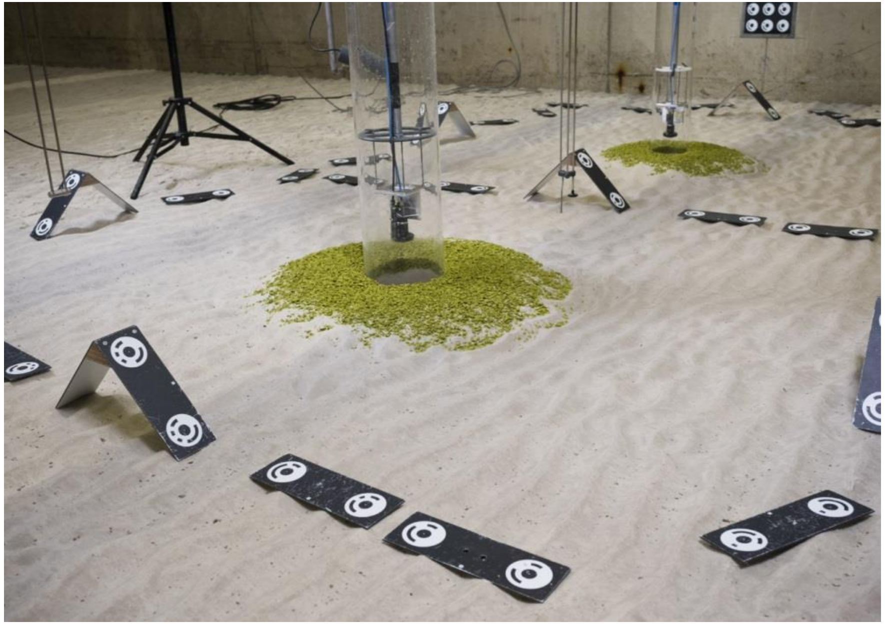
Ir. F.C.W. (Frank) van Erp

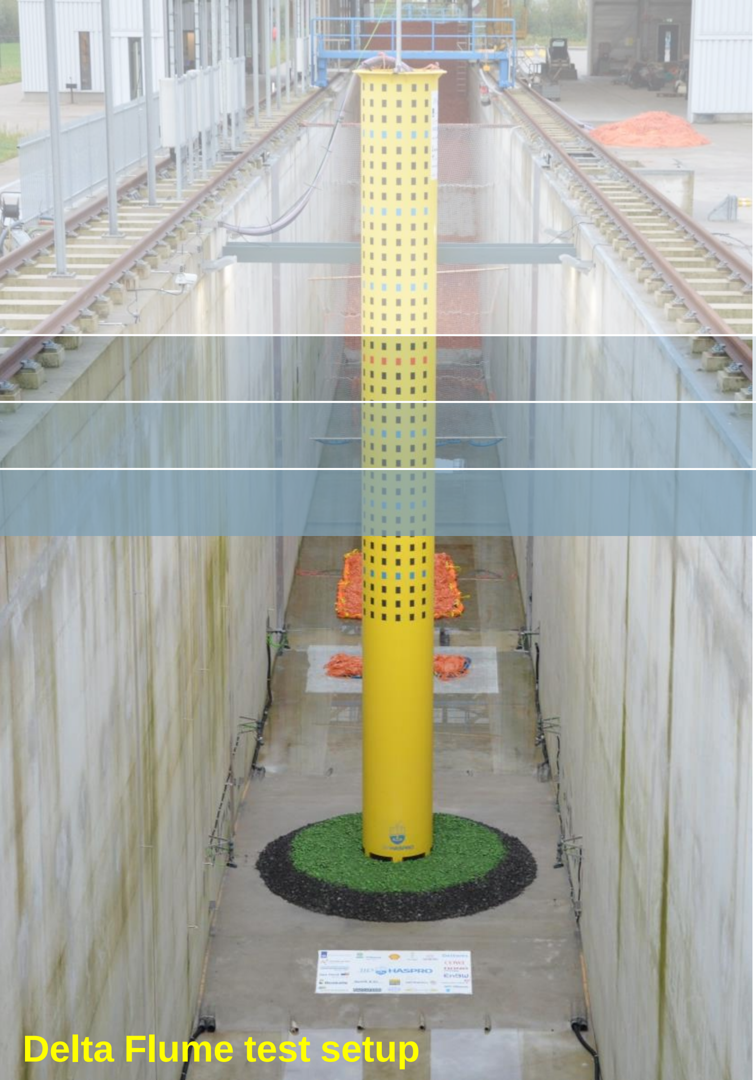
Welcome

- Introduction speaker and panel
- Goal of this webinar
- Agenda



Have a successful meeting!





Delta Flume test setup

Rijksdienst voor Ondernemend Nederland

Deltares

Scour and scour mitigation for Hollandse Kust (zuid)

recommendations for design of foundations and cables

Presenter: Tim Raaijmakers
Programme Manager
Offshore Engineering

Report 11200864-002-HYE-0001
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Introduction to webinar team

Presenter:

Tim Raaijmakers

Senior researcher/advisor, Programme Manager Offshore Engineering at Deltares

PhD researcher at TU Delft

Project Leader Scour and Scour Mitigation study HKZ

Moderators:

Frank van Erp

Senior advisor Offshore Wind Energy, RVO.nl (NEA)

Tom Roetert

Researcher/advisor Offshore Engineering at Deltares

Co-author of Scour and Scour Mitigation study HKZ

Cynthia Mors

Senior advisor Renewable Energy, RVO.nl (NEA)

Objectives of the scour and scour mitigation study

The objectives of this study are:

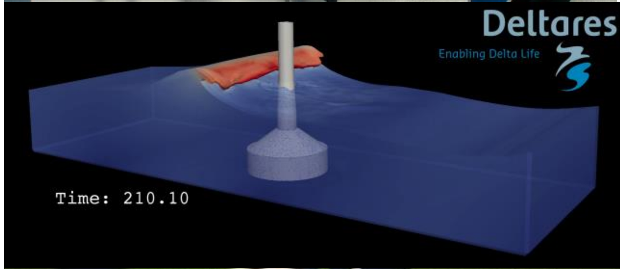
- To describe the scour conditions to be expected at Hollandse Kust (zuid) for typical wind farm-related structures*
- To provide a state-of-the-art overview of scour mitigation measures and their applicability at HKZ at these structures
- To provide guidance on how the morphodynamics should be taken into account for the selection of the structure's location and scour mitigation strategy

* Note that structure is here both interpreted as a wind turbine support structure and as an infield electricity cable. Offshore High Voltage Stations and the export cables are not considered part of the scope.

Deltares: facts and figures

Deltares is an **independent** institute for **applied research** in the field of **water, subsurface and infrastructure**.

- merger since 2008 of WL | Delft Hydraulics, GeoDelft and parts of TNO and Rijkswaterstaat
- applied research & specialist consultancy
- independent: serving companies and governments
- > 800 staff (mostly MSc/PhD), > 28 nationalities
- open-source policy: “dare to share”



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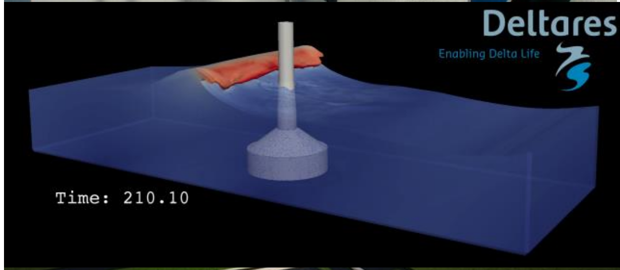

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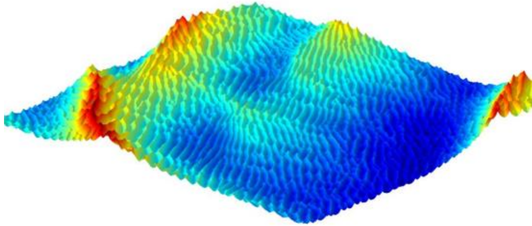
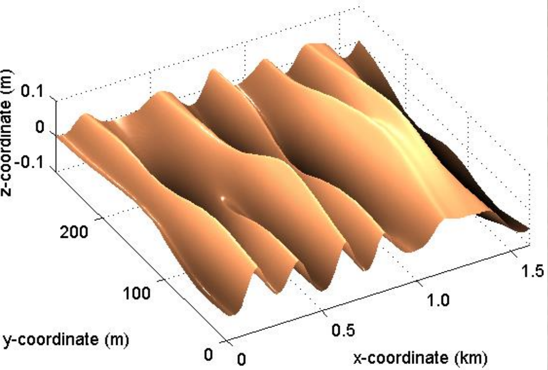
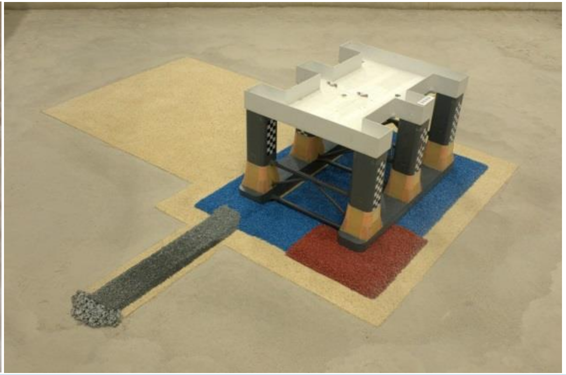
5. Examples for scour mitigation strategies
6. Cable routing in morphodynamic environments







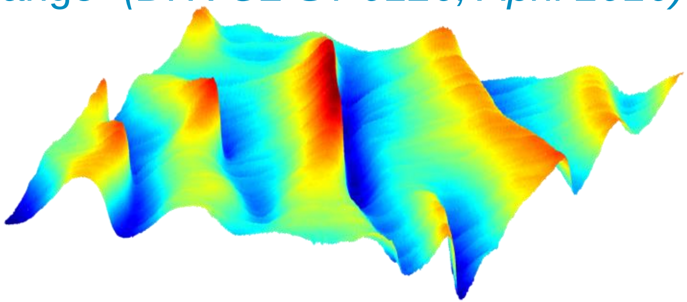
Seabed Morphodynamics - definitions

*“**Morphodynamics** refers to the study of the **interaction** and adjustment of the **seafloor topography and fluid hydrodynamic processes**, seafloor morphologies and dynamics involving the **motion of sediment**. Hydrodynamic processes include those of **waves, tides and wind-induced currents**.” [Wikipedia]*

Global / large-scale morphodynamics

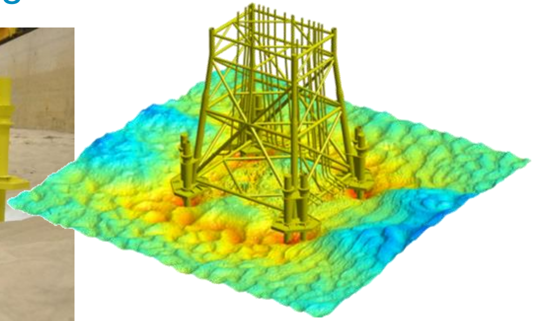
Sand waves in HKZ windfarm area

*In new DNV GL-guideline: “*general seabed level change*” (DNVGL-ST-0126, April 2016)*



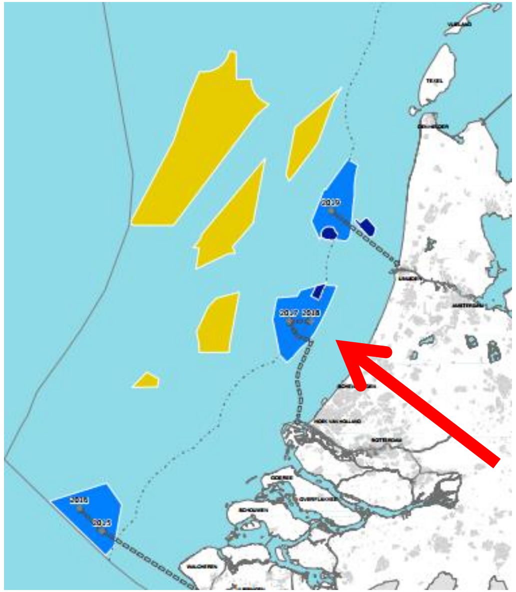
Local / small-scale morphodynamics

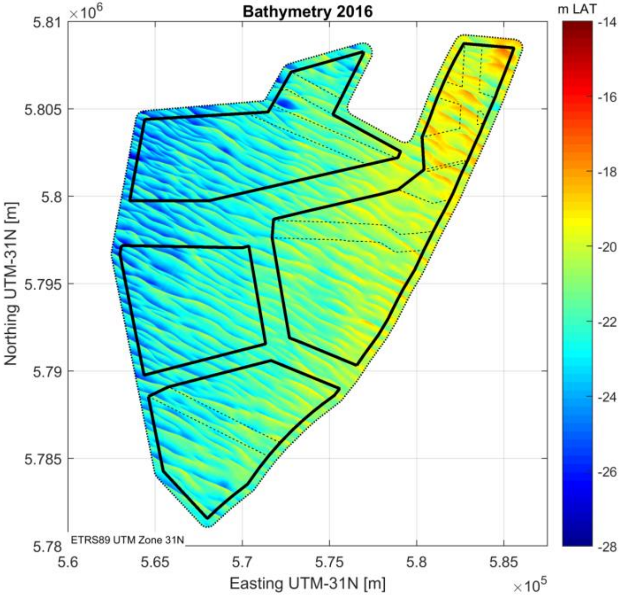
Local erosion = scour, e.g. around Offshore High Voltage Stations



Hollandse Kust (zuid) offshore wind farm

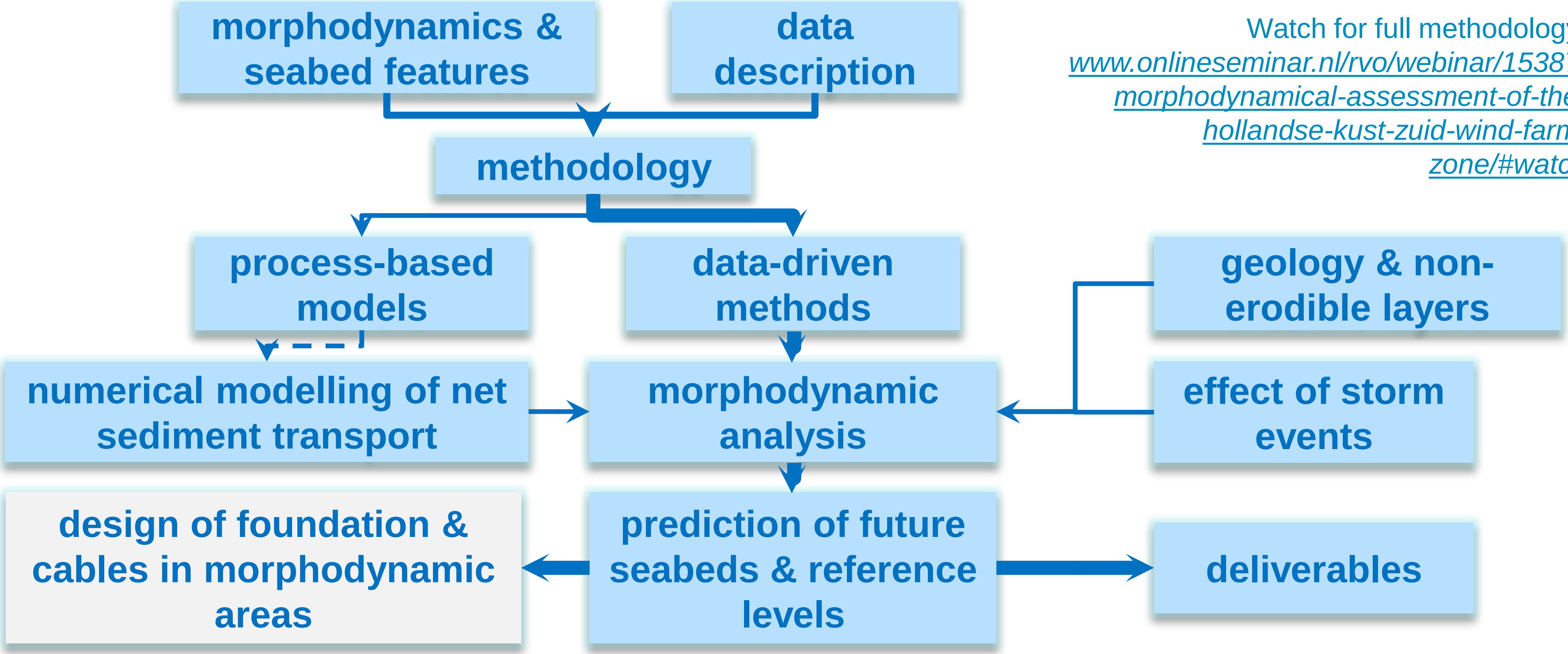
- Large wind farm area (1400 MW) offshore the Dutch Holland coast to be developed
- Area is characteriozed by active morphology in the form of sand waves



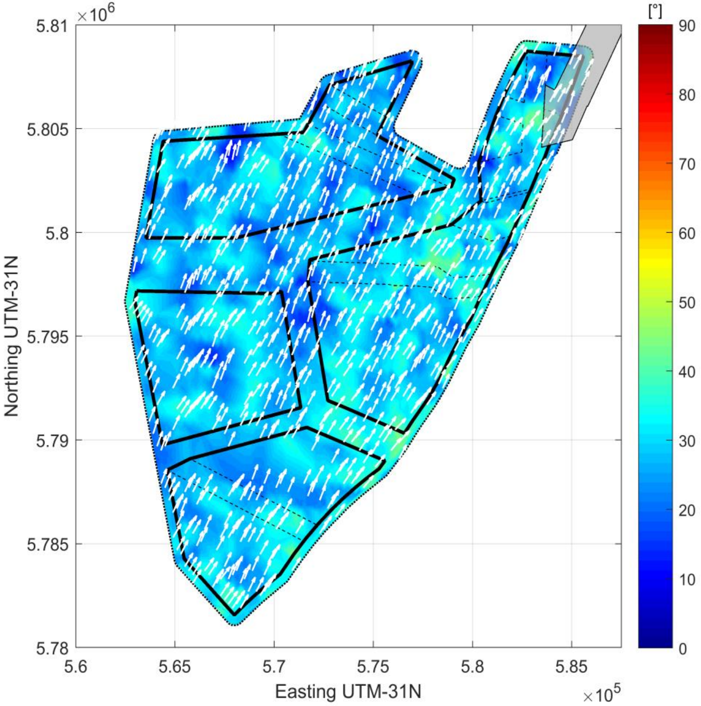


Methodology morphodynamic analysis

Watch for full methodology:
[*www.onlineseminar.nl/rvo/webinar/15387/morphodynamical-assessment-of-the-hollandse-kust-zuid-wind-farm-zone/#watch*](www.onlineseminar.nl/rvo/webinar/15387/morphodynamical-assessment-of-the-hollandse-kust-zuid-wind-farm-zone/#watch)



Sand wave migration direction and speed in HKZ



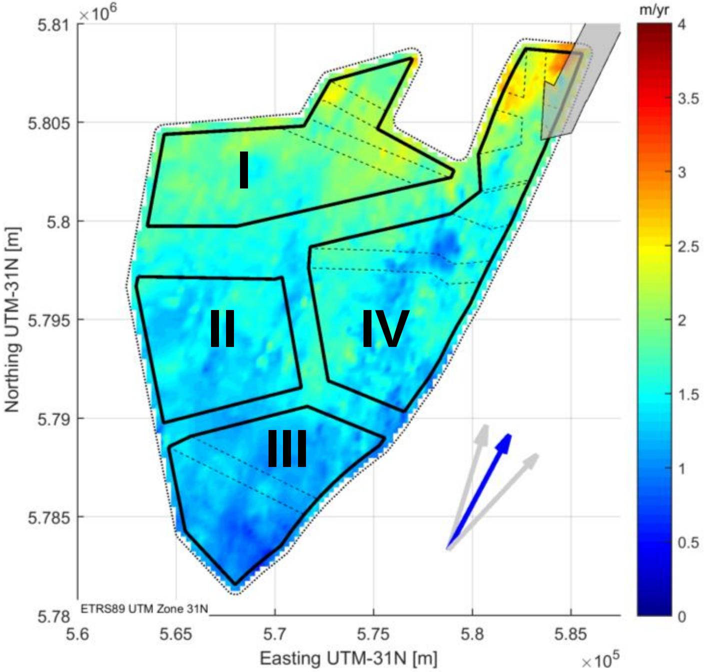
Sand wave migration direction:

Main migration directions of approximately **28°N** with variations up to about **20-30°** around the main axis

Sand wave migration speed:

south-north trend in migration speed over HKZ WFZ

sand wave migration



Lowest and Highest SeaBed Levels

Lowest SeaBed Level (LSBL)

The lowest possible seabed level during the lifetime of the wind parks (i.e. 2016-2051)

\+ Static Seabed Level
\- Lower envelope of Sand Wave Field until 2051
\- Downward uncertainty band

Lowest SeaBed Level (LSBL)

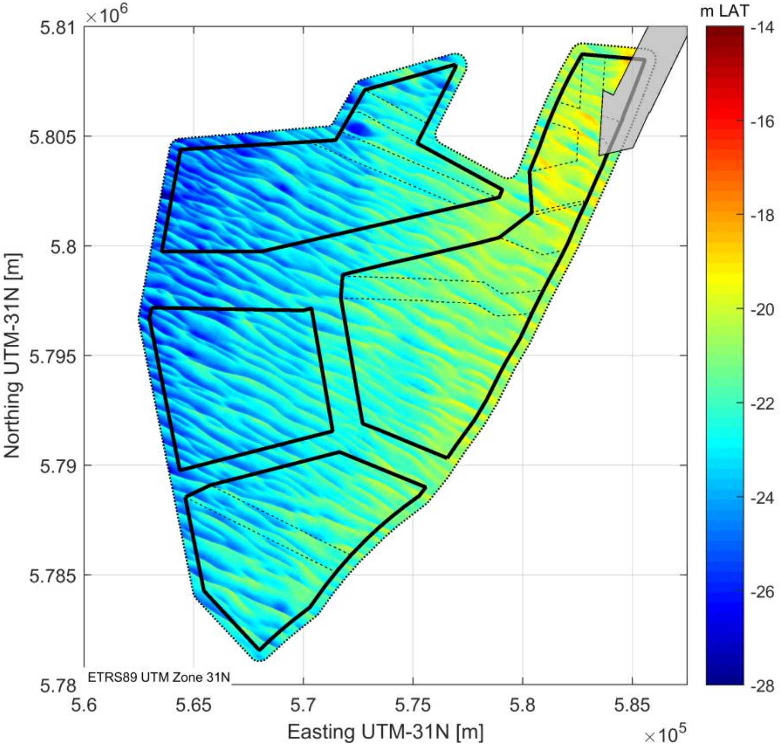
Highest SeaBed Level (HSBL)

The highest possible seabed level during the lifetime of the wind parks (i.e. 2016-2051)

\+ Static Seabed Level
\+ Upper envelope of Sand Wave Field until 2051
\+ Upward uncertainty band

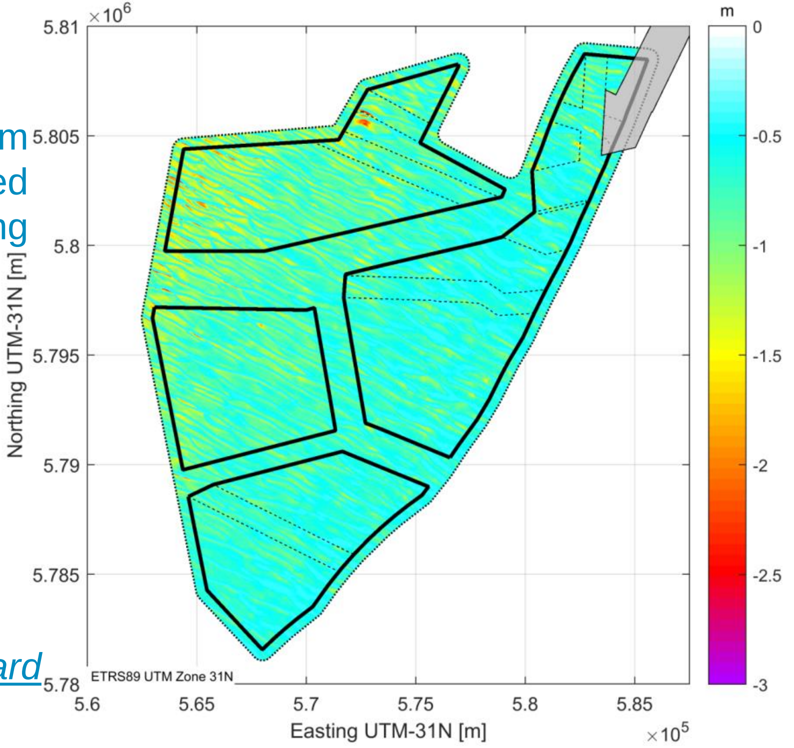
Highest SeaBed Level (HSBL)

LSBL and maximum potential seabed lowering



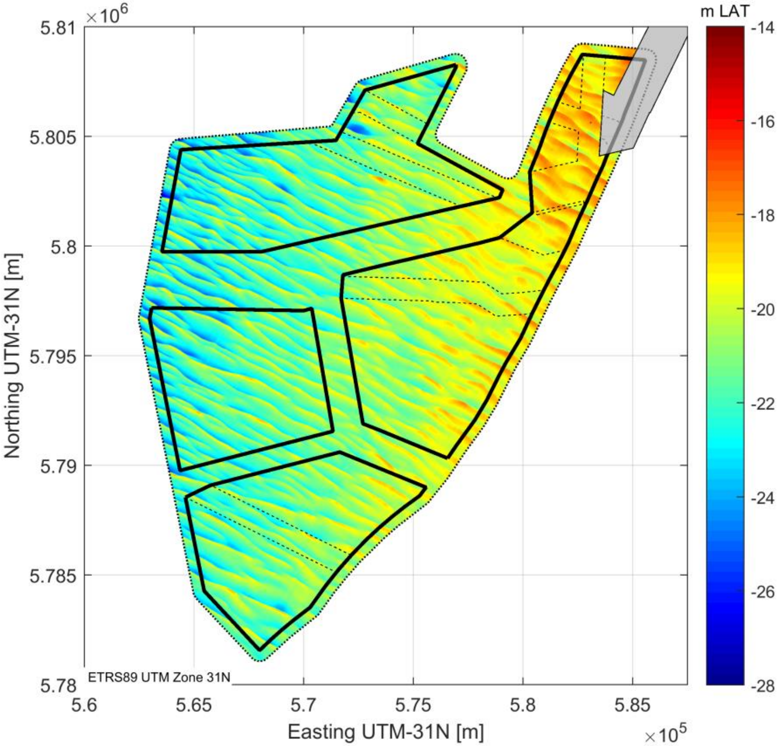
Lowest Seabed Level

Maximum Seabed Lowering



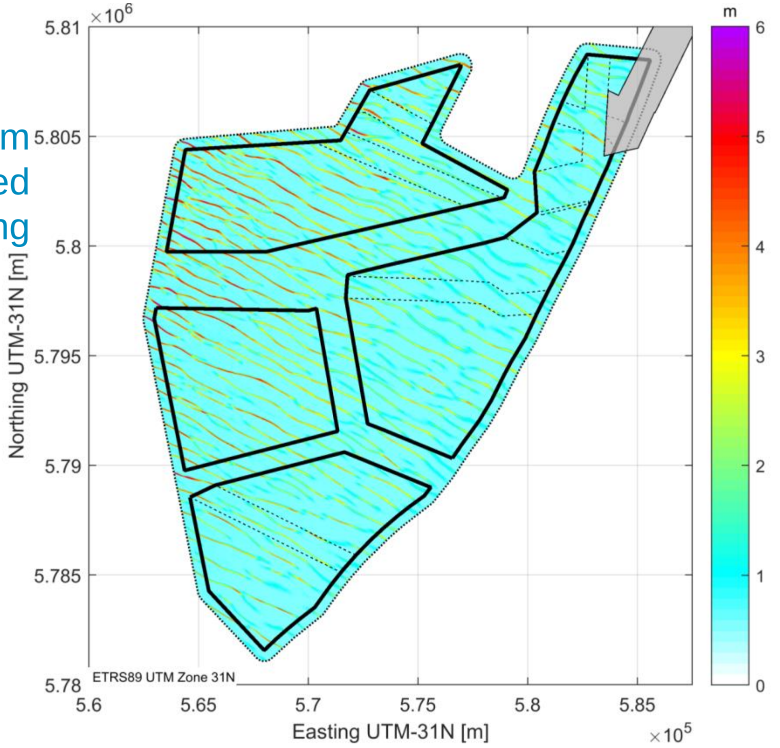
cumulative downward seabed movement

HSBL and maximum potential seabed rising



Highest Seabed Level

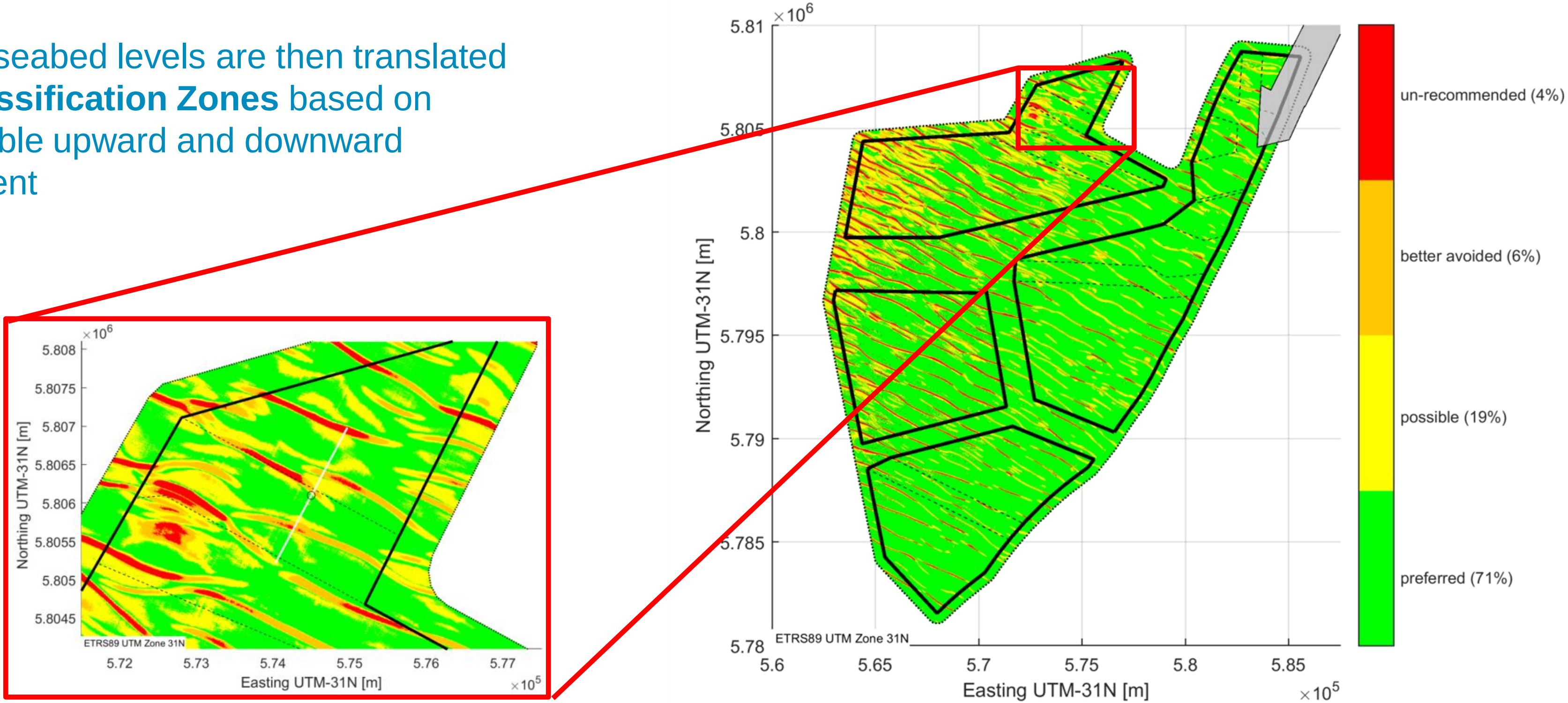
Maximum Seabed Rising



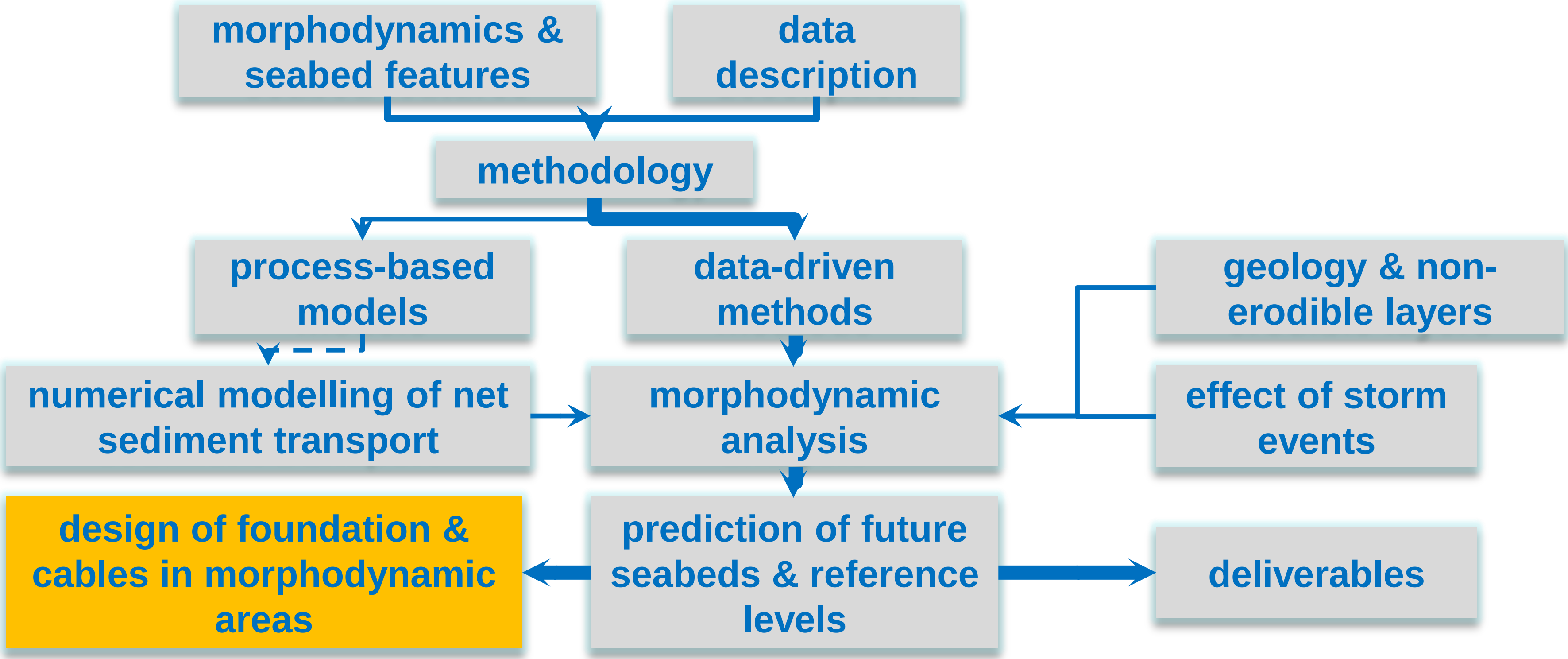
cumulative upward seabed movement

Classification zones for Hollandse Kust (zuid)

Design seabed levels are then translated into **Classification Zones** based on acceptable upward and downward movement



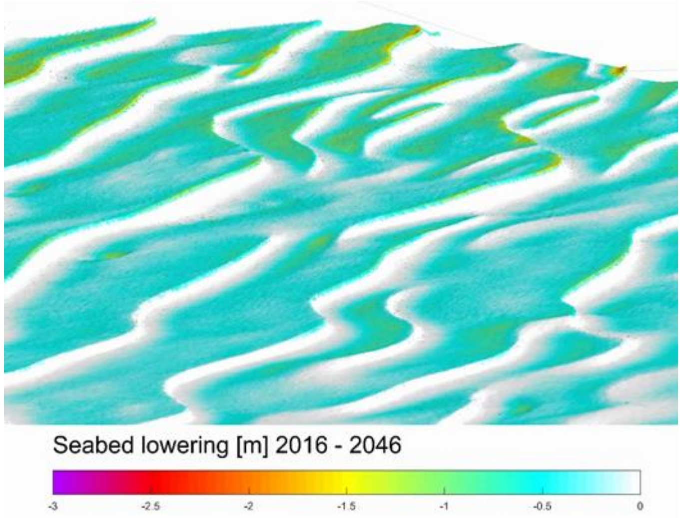
Methodology morphodynamic analysis



Summarizing seabed lowering and rising in HKZ

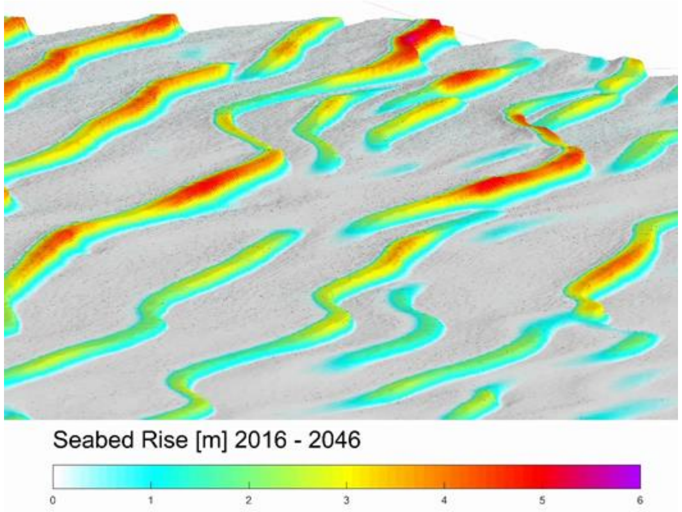
Predicted **seabed lowering** plotted on top of migrating seabed:

- relatively gentle seabed lowering at stoss sides of sand waves



Predicted **seabed rising** plotted on top of migrating seabed:

- significant seabed rising but only just downstream of lee sides of sand waves



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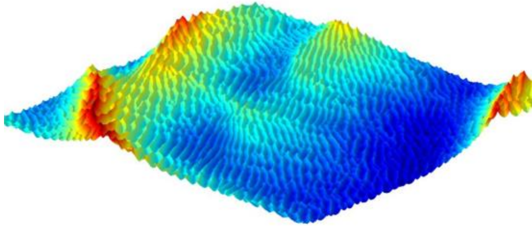
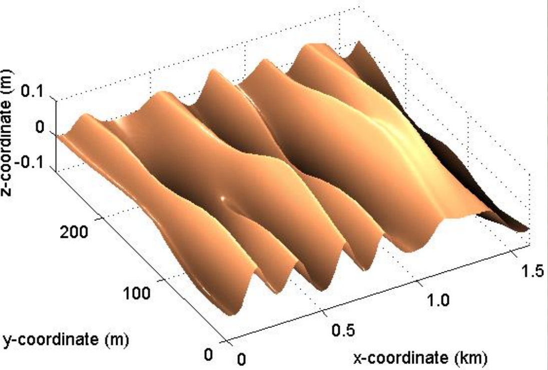
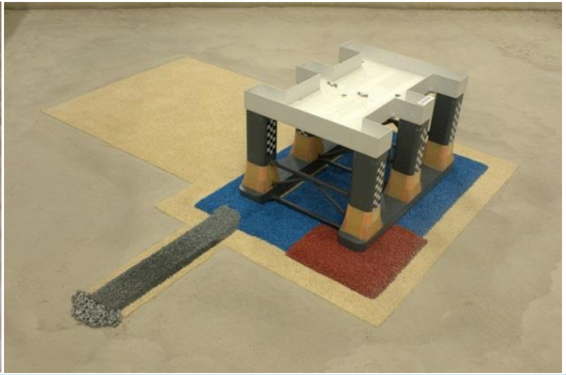
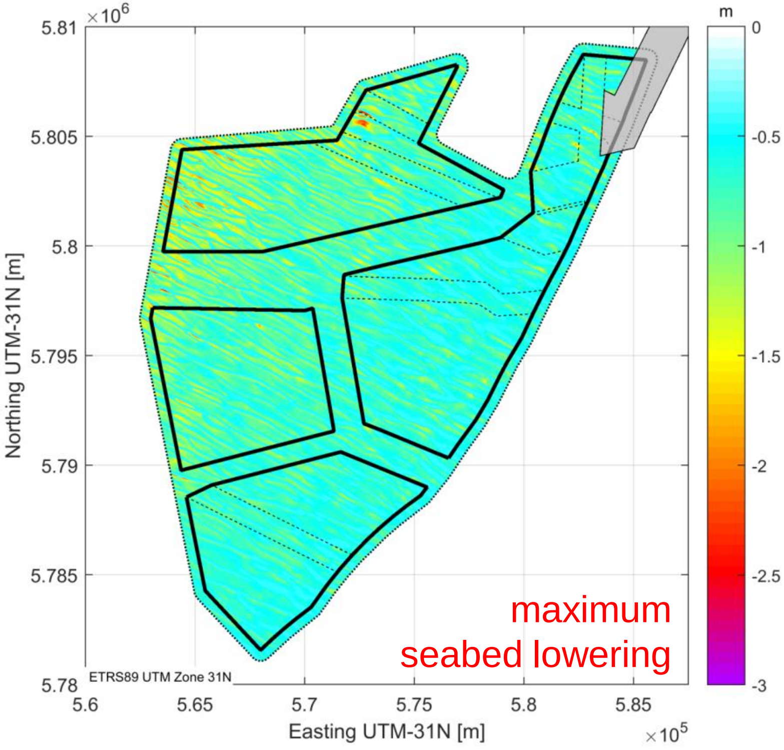






Scour mitigation strategies excluding morphodynamics

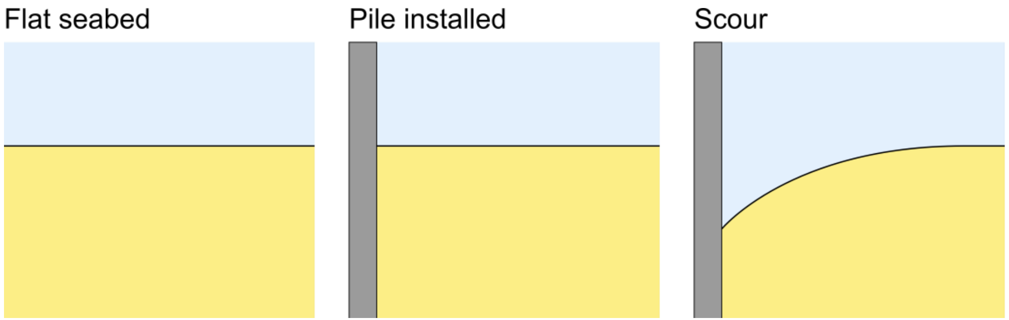
- Before including the full complexity of autonomous morphological processes, first scour mitigation strategies will be developed for (more or less) stationary seabeds
- For HKZWFZ this means that the sites need to be selected that are characterized by less than 1 m seabed change during the lifetime of the wind farm
- Whether and when an offshore structure needs to be protected is a matter of cost efficiency (cost of scour protection vs extra material consumption) and risks.



Scour mitigation Strategy A – Free scour development

Scour mitigation strategy A* allows for free scour development and is often considered when:

- It can be proven that the seabed is not or hardly erodible or non-erodible layers are present at limited depth below the seabed
- The seabed is only erodible under extreme conditions (wave-dominated scour vs current-dominated scour)
- The foundation type is not/hardly sensitive to scour development (jackets vs monopiles)

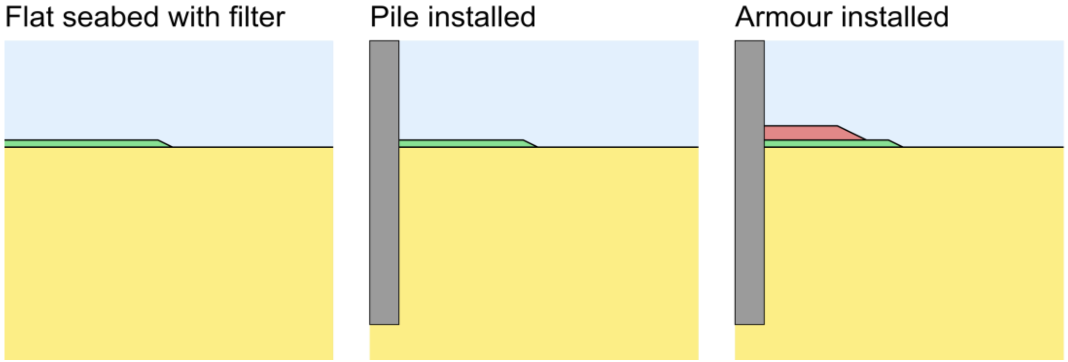


* Note that all schematizations are showing monopiles, but the strategies are valid for all foundation types

Scour mitigation Strategy B – Immediate scour protection

Scour mitigation strategy B is based on an immediate installation of scour protection and is often considered when:

- the seabed is well erodible
- (for a monopile): the costs of additional steel consumption exceed costs of scour protection
- the foundation type is a “sit-on-bottom”-type such as a Gravity Based Structure
- the foundation type has a limited penetration depth such as a Suction-Bucket-Jacket

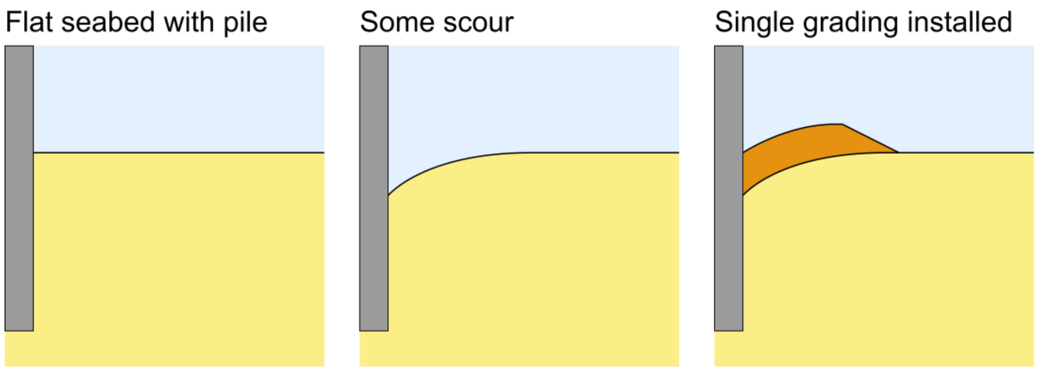


Example of pre-filter installation and post-armour installation; other installation sequences are possible as well

Scour mitigation Strategy C – Monitor and React

Scour mitigation strategy C is based on first allowing scour development up to a pre-defined level and then install a scour protection inside the scour hole and is often considered when:

- the scour protection is to be installed in a highly morphodynamic area
- the top soil layer does not really contribute to the lateral bearing capacity
- a more sheltered position of the scour protection is preferred (e.g. breaking waves)
- scour development is more severe than anticipated (Strategy A -> Strategy C)



Scour mitigation strategies including morphodynamics

When a wind farm is planned in a morphodynamic area such as HKZ, there are two causes for having to take morphodynamics into account in the scour mitigation strategies:

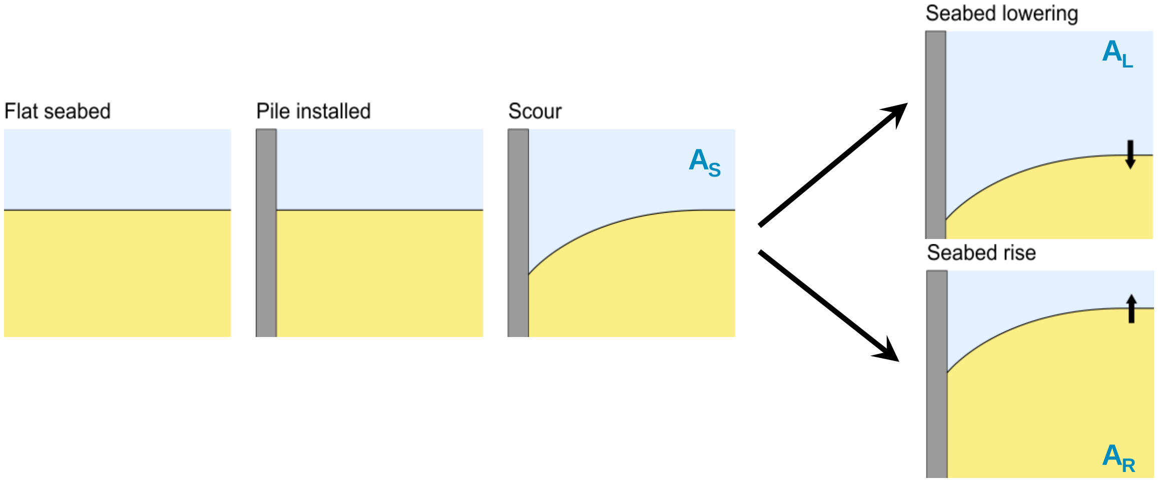
- morphodynamics are not taken into account when the wind farm layout is determined

  (e.g. layout is only based on wind yield and morphodynamic consequences need to be dealt with afterwards)
- foundations are deliberately planned on locations with expected seabed changes

  (e.g. optimizing for steel consumption and dealing with morphodynamics in scour mitigation strategy)

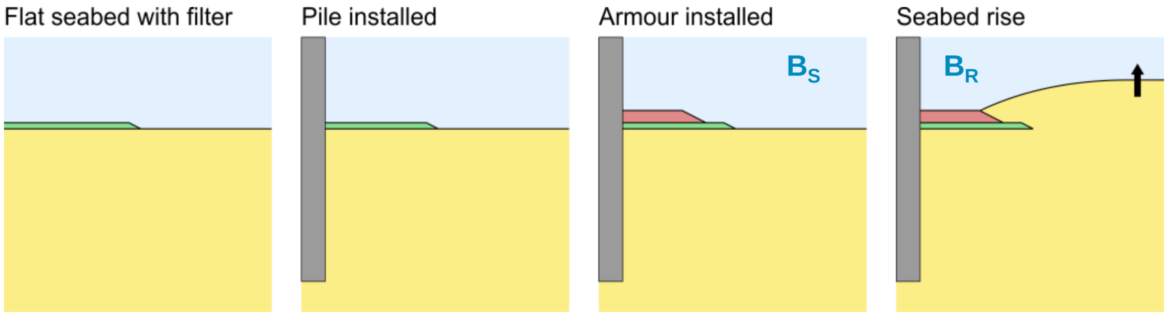
Scour Mitigation Strategy A – Free scour development

- For Strategy A the consequences of seabed lowering in relation to free scour development are minor in HKZ ($S_{pile} > \Delta_{seabed\ lowering}$)
- Timescales of autonomous seabed changes >> timescales of scour development
- Scour hole will be able to follow the changing seabed (due to this difference in timescales)

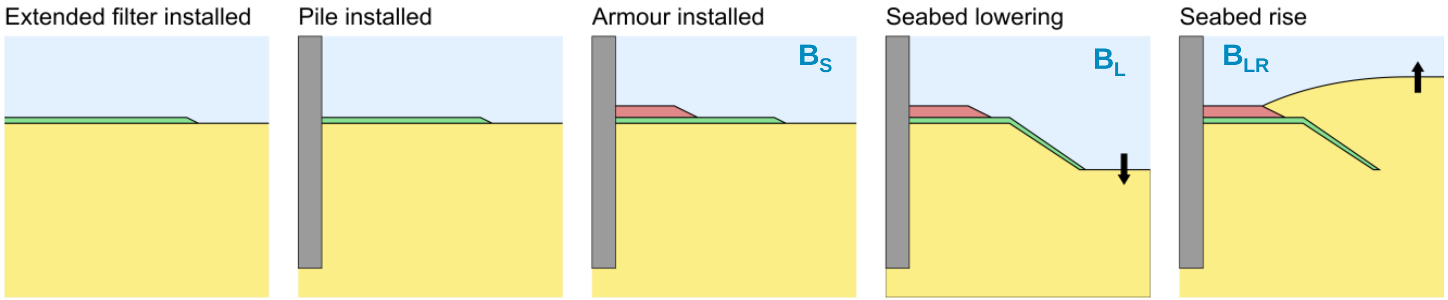


Scour Mitigation Strategy B – Immediate scour protection

- Immediate scour protection with rising seabed

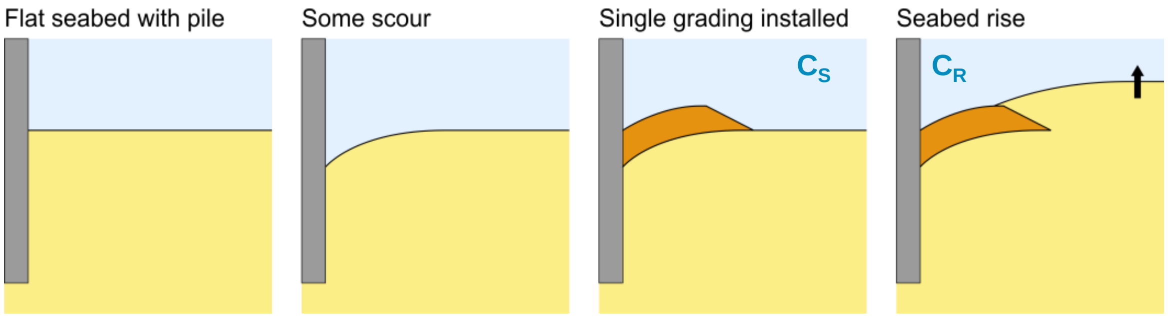


- Immediate scour protection with lowering seabed

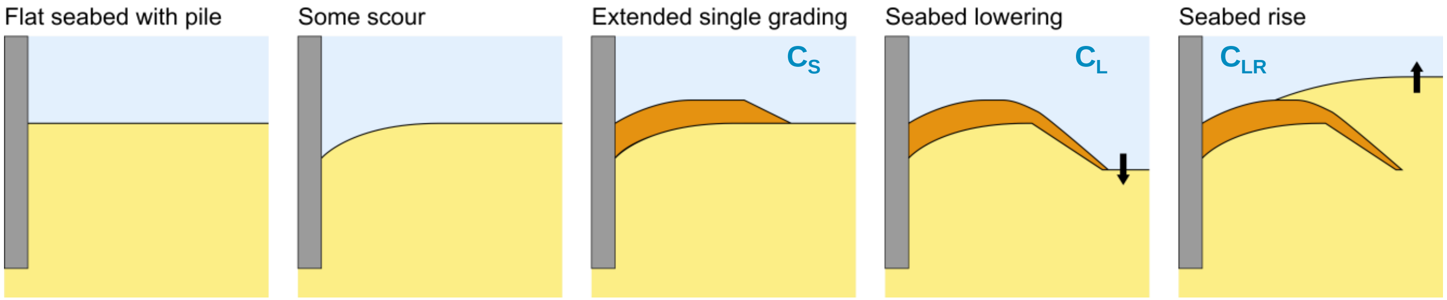


Scour Mitigation Strategy C – Monitor & react

- Monitor and react with rising seabed



- Monitor and react with lowering seabed (…..and perhaps later rising again)



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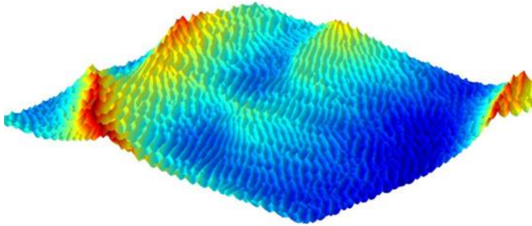
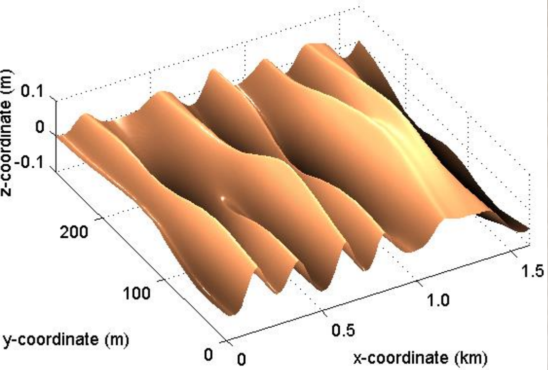
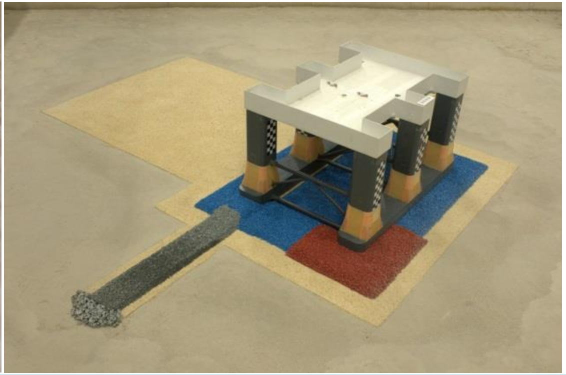


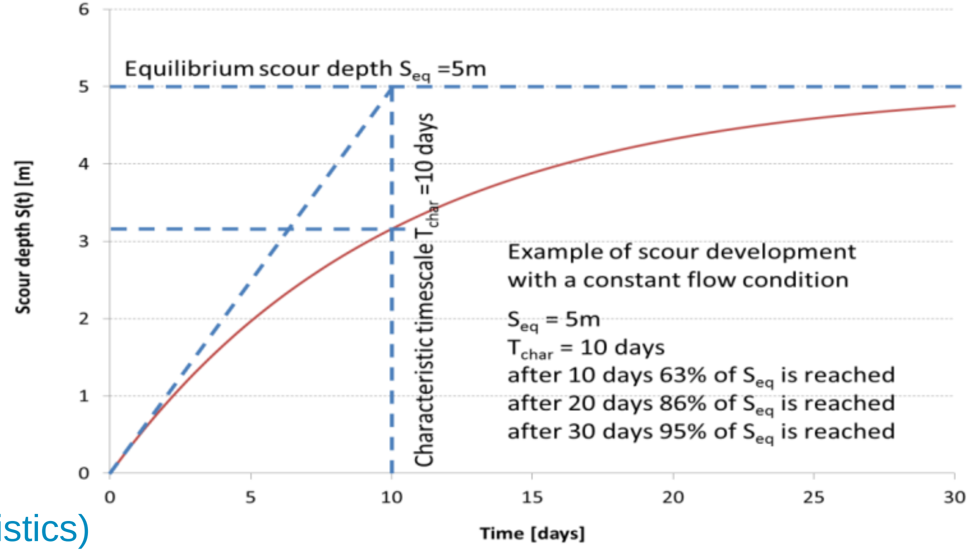




Scour development in time

Scour development in time S(t) follows an exponential relation until equilibrium:

$$\frac{S(t)}{S_{eq}} = 1 - \exp\left(-\frac{t}{T_{char}}\right)$$



in which:

S_{eq} = equilibrium scour depth

T_{char} = characteristic timescale

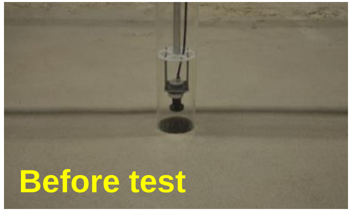
Both parameters are dependent on:

- ✓ water depth
- ✓ seabed conditions
- ✓ pile diameter (or more general structure characteristics)
- ✓ hydrodynamic climate (distinction between wave- and current-dominated conditions)

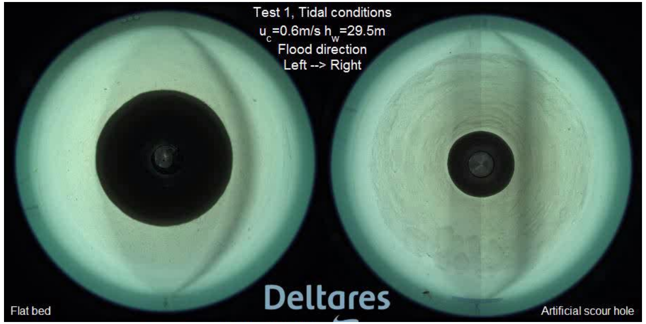
For all possible combinations S_{eq} and T_{char} have to be determined!

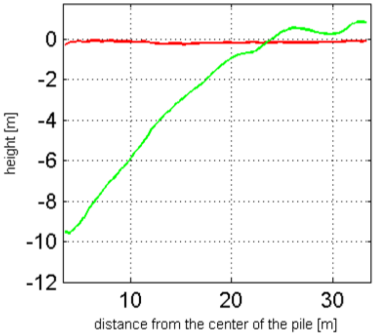
Scale model tests for scour at Deltares

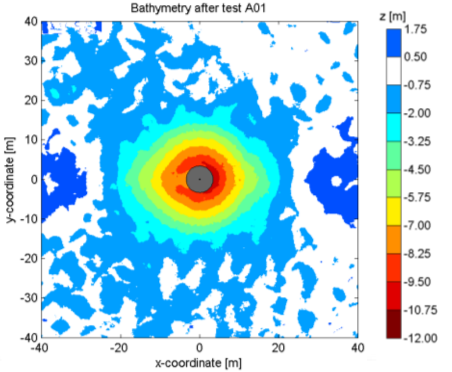
Transparent scale model of monopile equipped with camera and fisheye lens



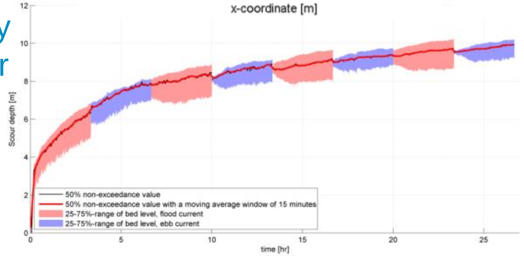
View from inside the monopile looking at seabed lowering = scour



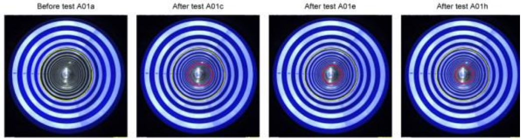




3D-stereophotography results in spatial scour patterns

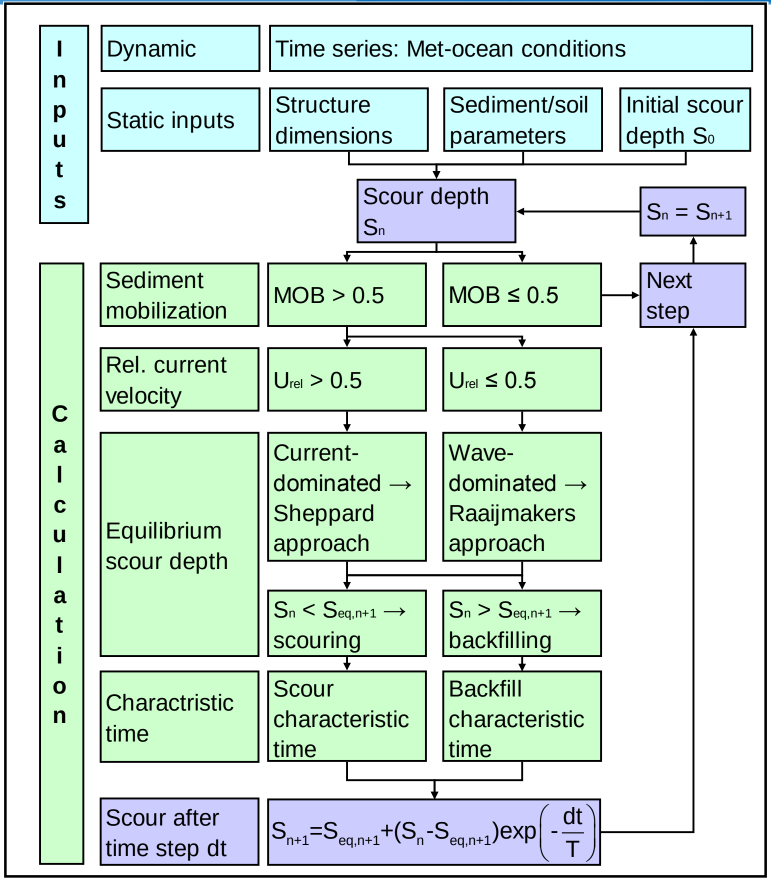


Calibration of camera images and extracting of bed interface results in quantitative scour development in time



Scour Prediction Model

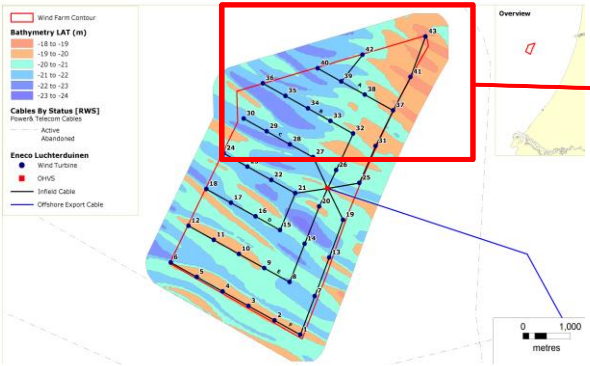
- Calculation model to predict dynamic scour development
- Location- and structure-dependent scour prediction
- Distinguishes between wave- and current-dominated scour
- Allows for scouring and backfilling
- Calculates years of scour development in < 1 minute
- Completely based on scale model tests and therefore required validation against field data!

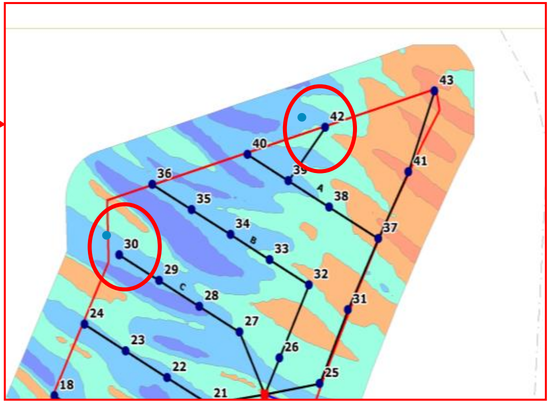


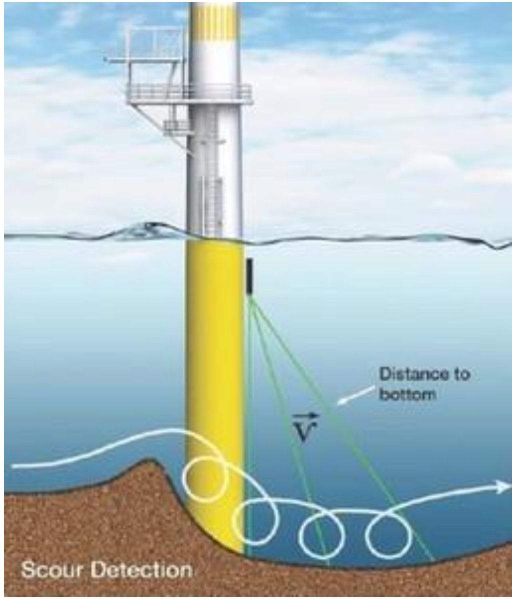
Flow Chart of Deltares' Scour Prediction Model

Field Measurement Campaign in Luchterduinen

- Field measurements at 2 unprotected monopiles in Eneco Luchterduinen OWP
- To validate the equilibrium scour depths and characteristic timescales of the Deltares' Scour Prediction Model
- Simultaneous hydrodynamic data were collected as input for the Scour Prediction Model
- One year of measurements allows for validation of the SPM for a wide range of conditions (current- and wave-dominated)







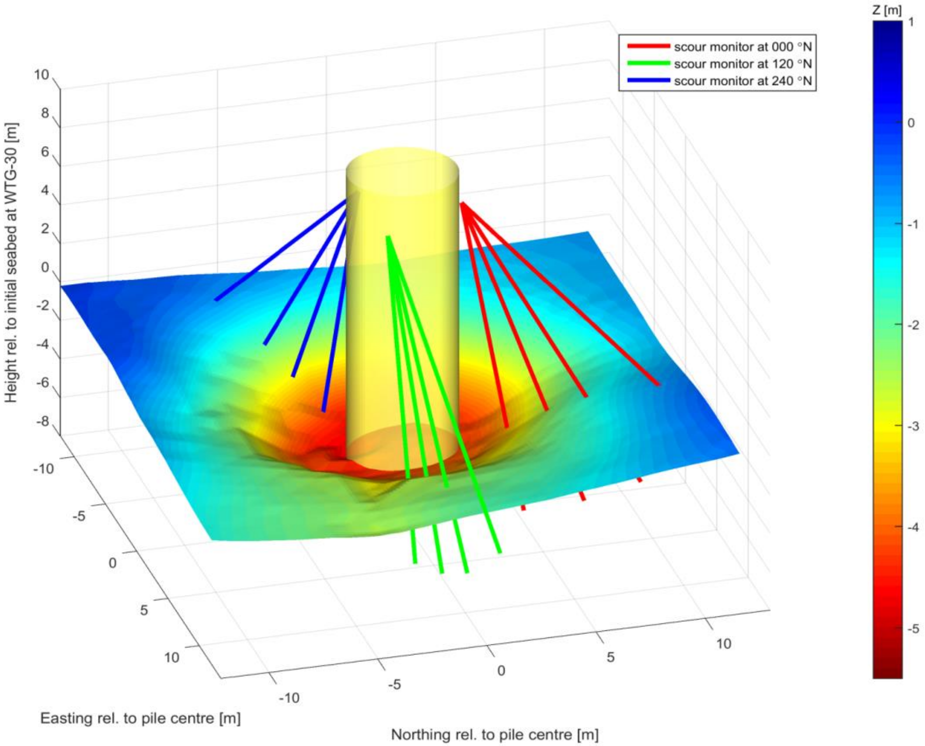
Setup of measurement campaign

Scour measurements

- 3 Nortek scour monitors per pile
- 4-beam echo sounder (12 signals / pile)
- under beam angles of 10, 20, 30 and 45°
- supplemented with multibeam surveys

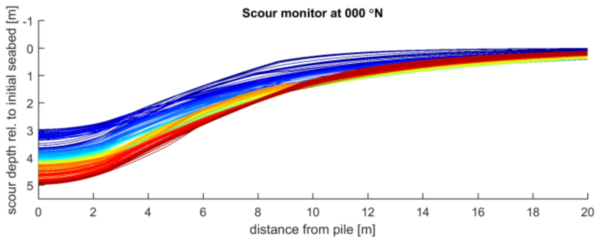
Hydrodynamics

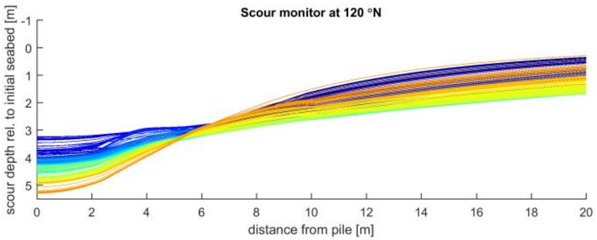
- 3 wave buoys in wind farm
- ADCP for current velocity profile
- numerical models to fill in gaps

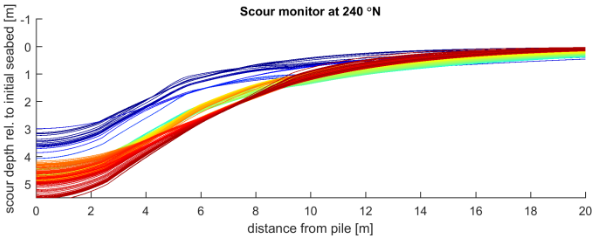


Scour hole profiles: development in 1 year

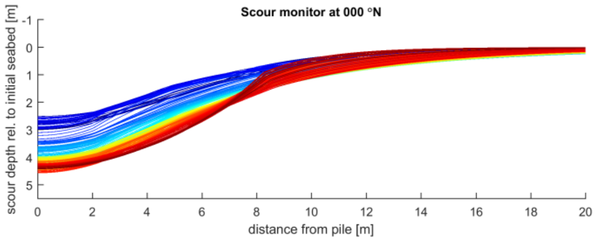
Monopile 1

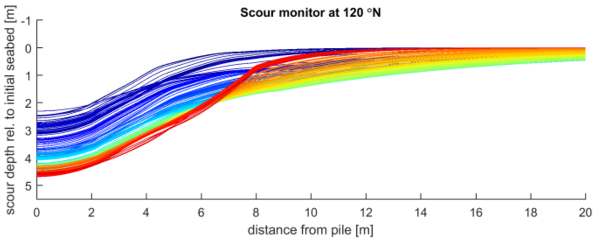


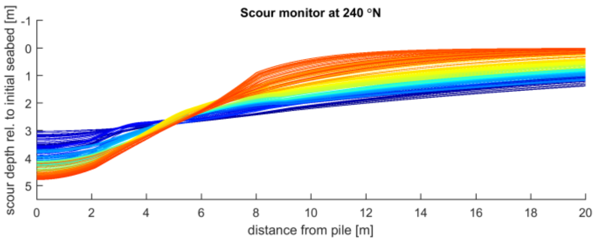




Monopile 2







Scour hole profiles: development in 1 year

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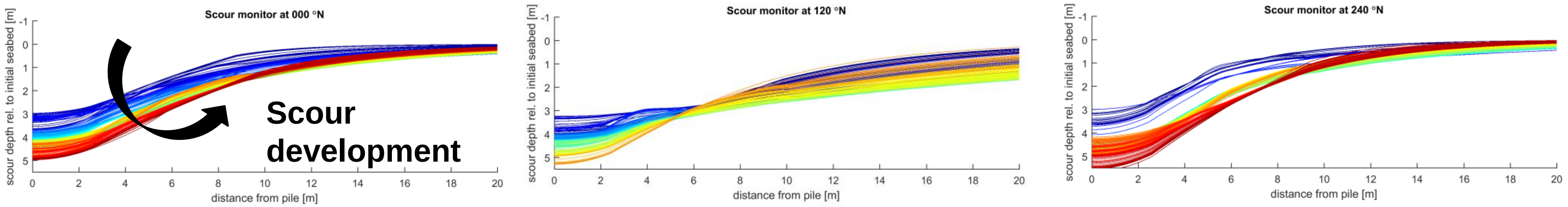
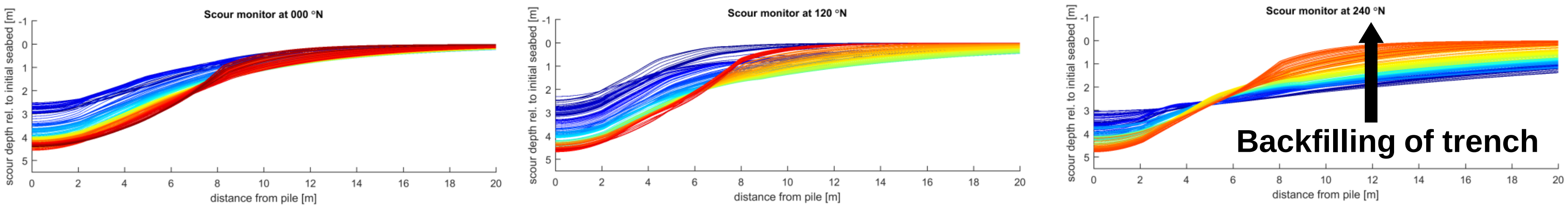


Monopile 2



Scour hole profiles: development in 1 year

Monopile 1

- Scour development until dynamic equilibrium takes about 1-1.5yr (in Luchterduinen!)
- Backfilling of the 2-3m deep cable trench took about 9-10 months
- The scour pit is now about 5-5.5m deep = 1.0-1.1*D_{pile}
- The dynamic scour depth will probably stabilize around 6m = 1.2*D_{pile} (according to design)
- The diameter of the scour pit is about 5*D_{pile}
- The side slopes are about 1:2
- The scour holes in Luchterduinen are very similar to the scour holes in the laboratory tests on scale ~1:40!

Current velocity

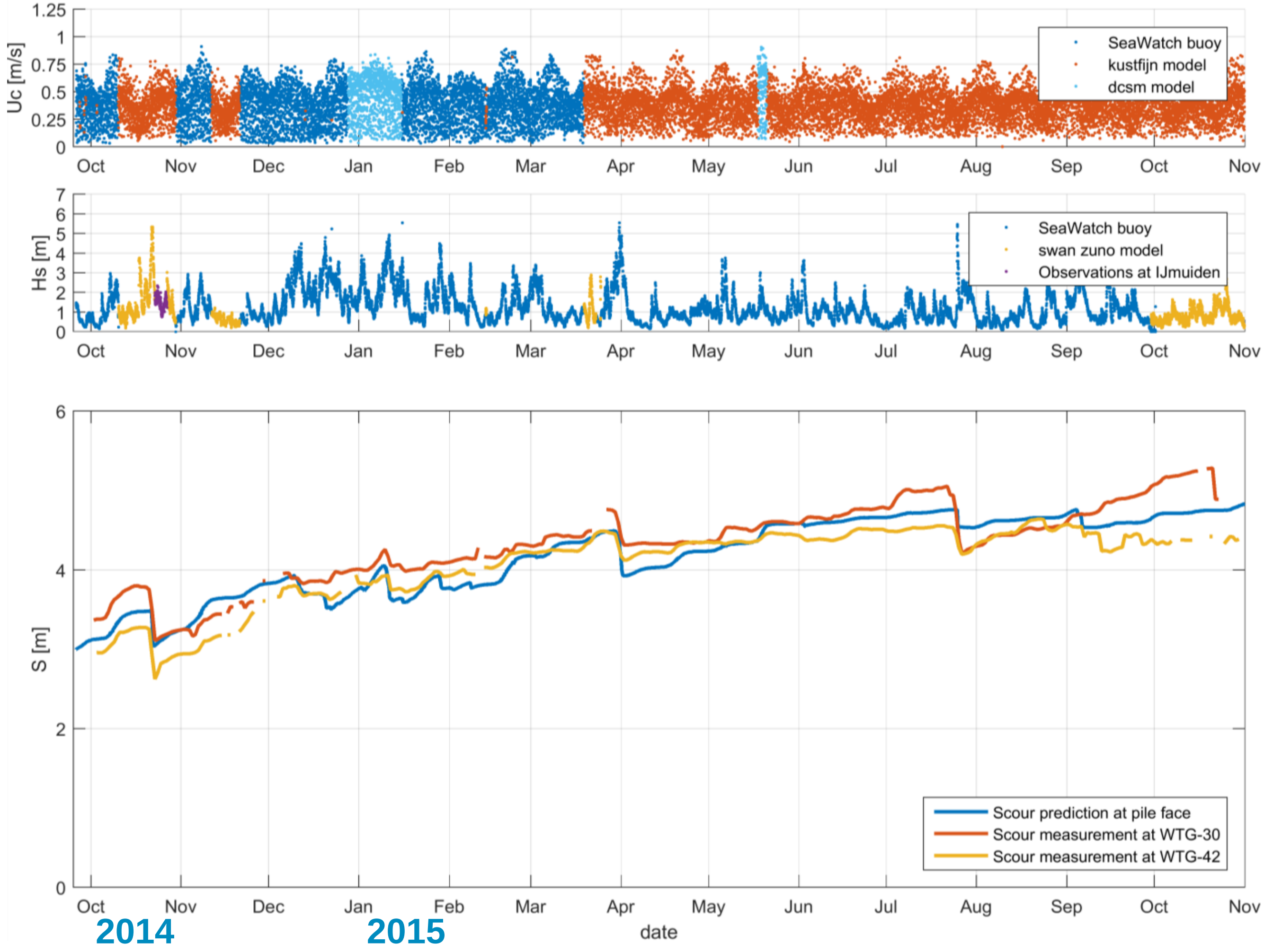
U_c [m/s]

Significant wave height

H_s [m]

Scour depth

S [m]



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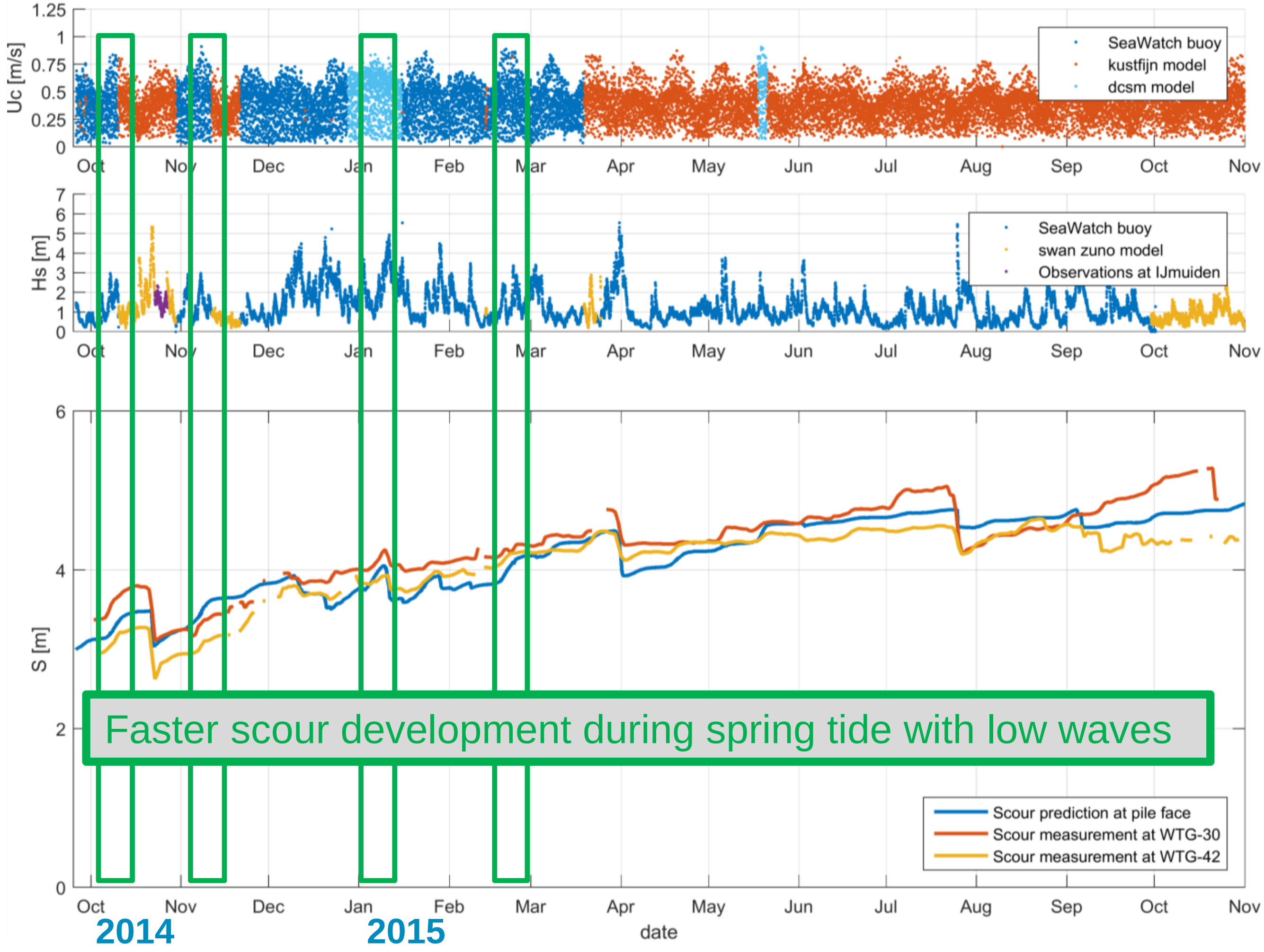

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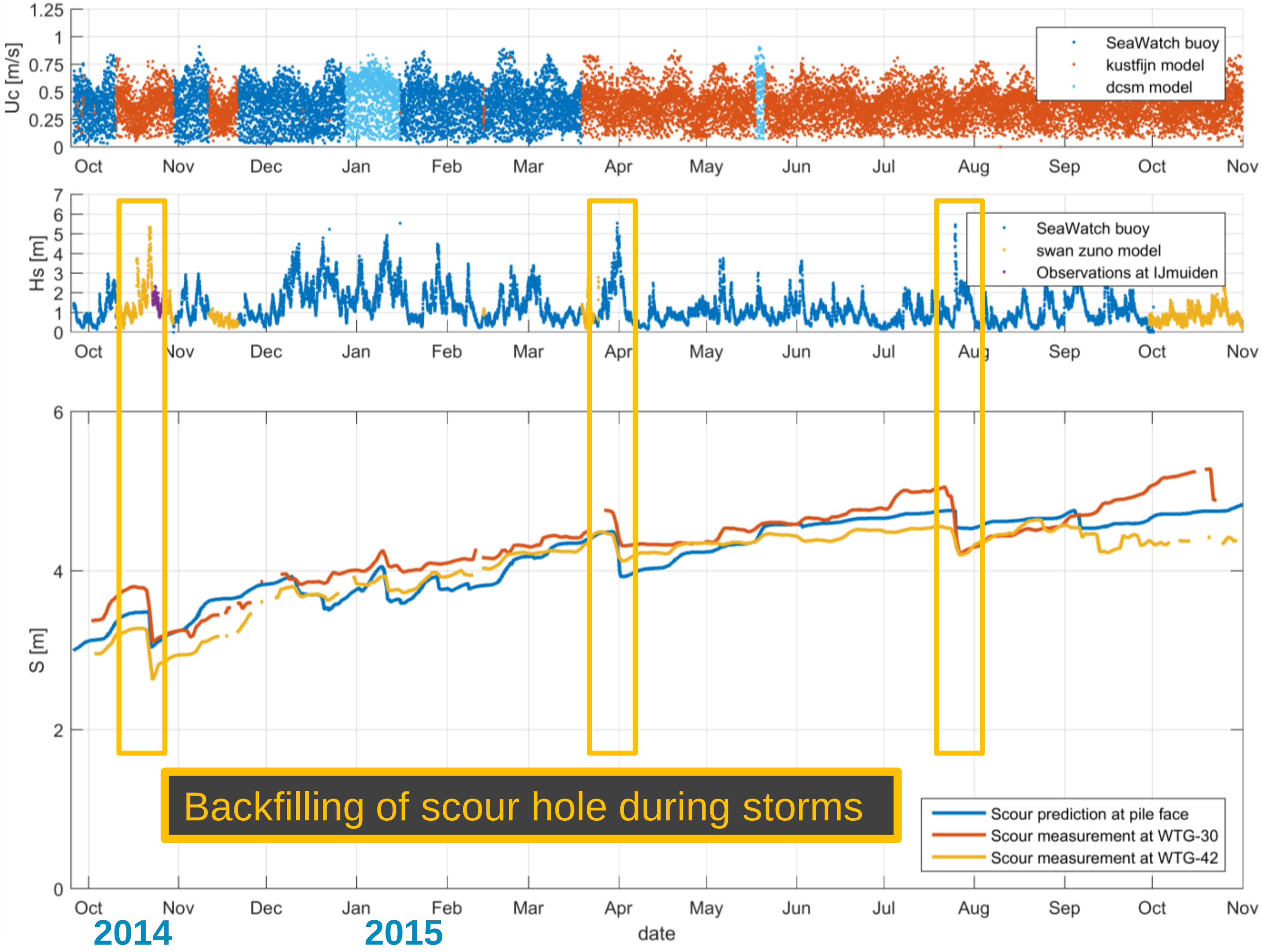


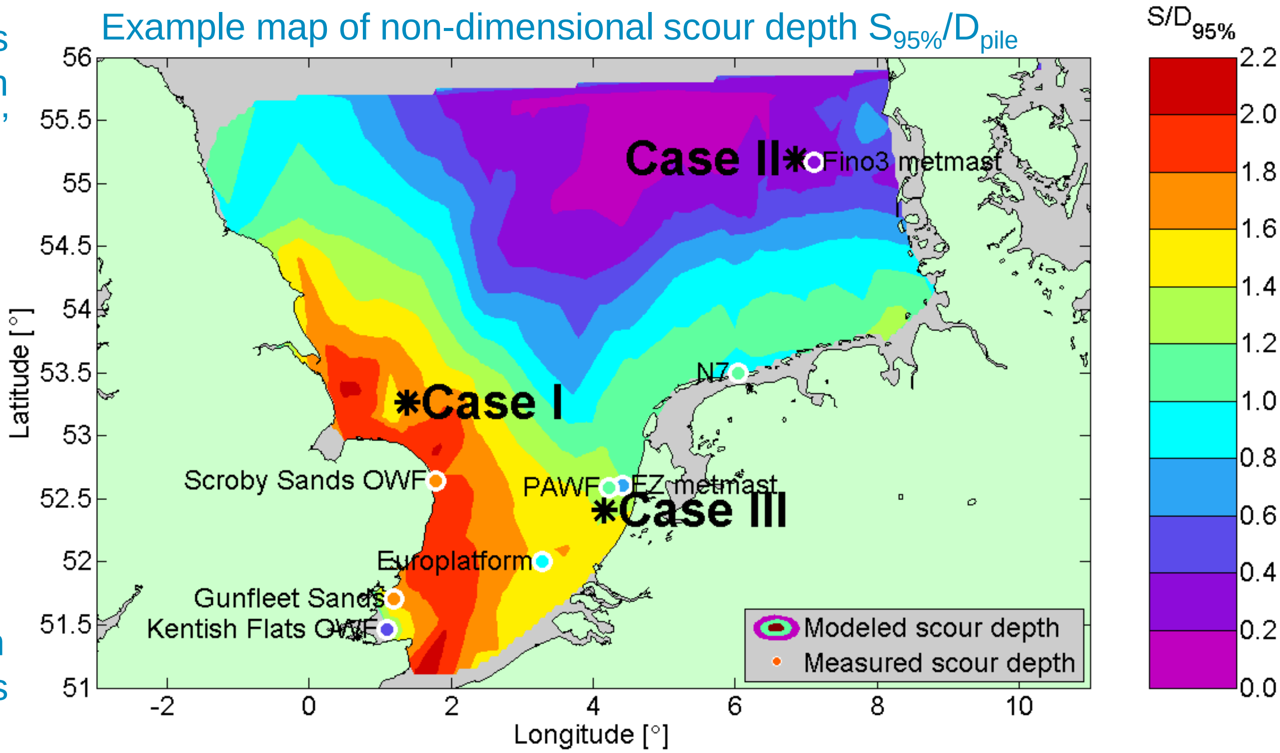
Safe upperbound for dynamic scour depth: $S_{95\%}/D_{pile}$

Scour predictions for monopiles situated in the southern North Sea, performed with Deltares' Scour Prediction Model

Model assumptions:

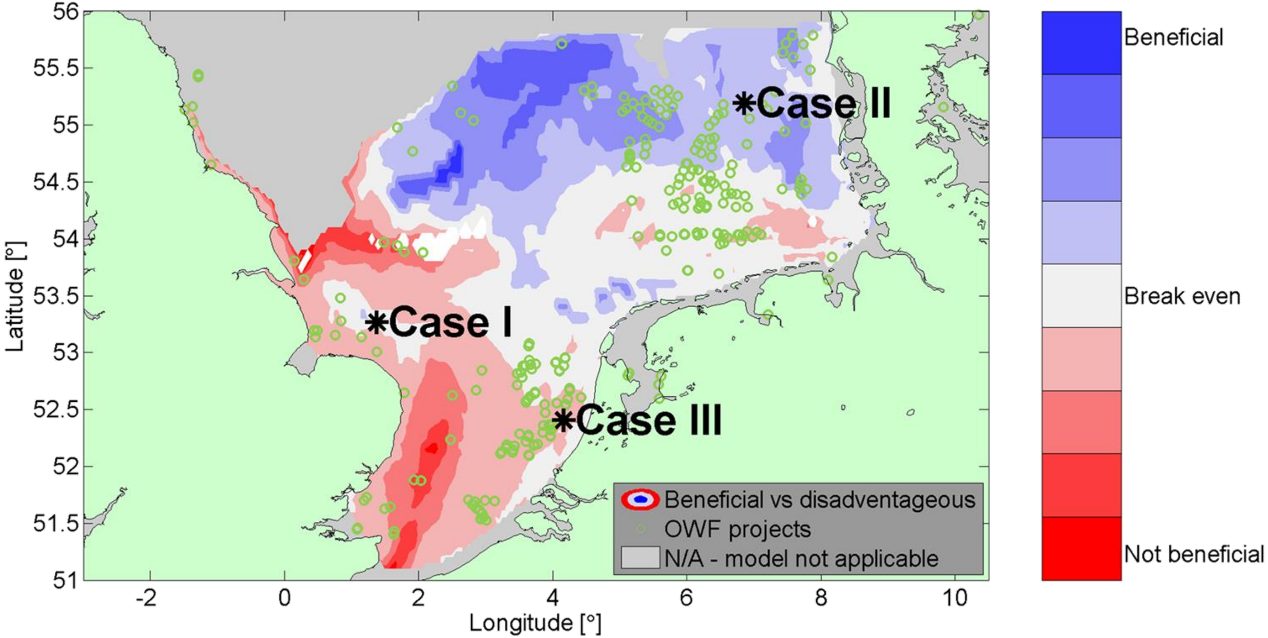
- Non-cohesive soil (= sandy seabed)
- Based on >100 simulations with different hydrodynamic time series (different starting times) per grid point
- Valid for unprotected monopiles; small differences in map for different pile diameters

Example map of non-dimensional scour depth $S_{95\%}/D_{pile}$



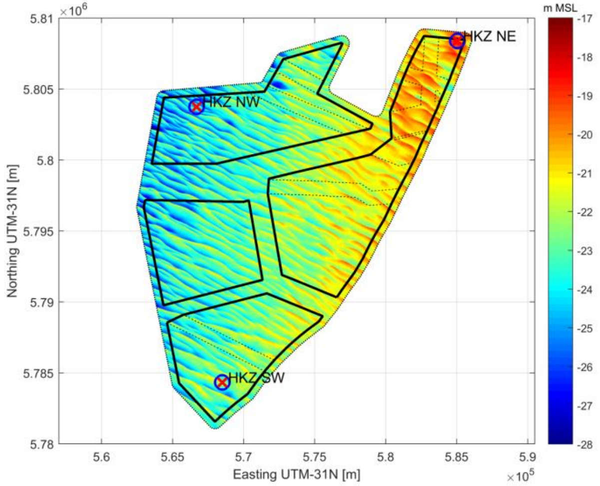
Scour: to protect or not to protect?

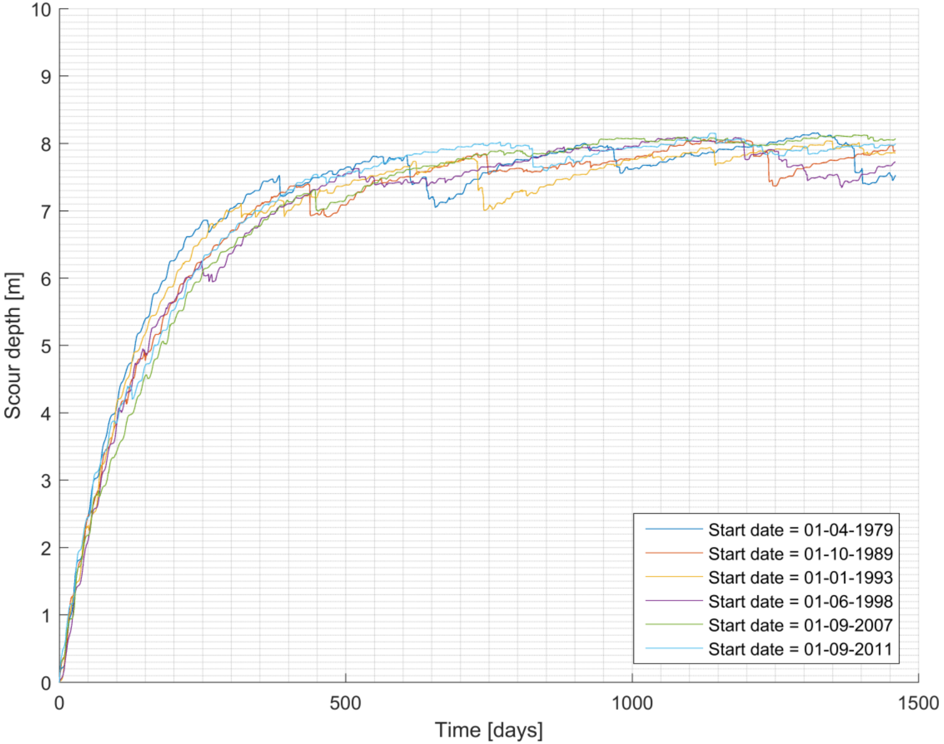
- Example of cost comparison map, showing for a certain turbine size and pile diameter whether it is more cost efficient to extend the pile or to install a scour protection
- Blue colours mean that there is a real potential for leaving out scour protection
- Exact maps will differ per turbine and foundation type



Scour predictions for HKZ

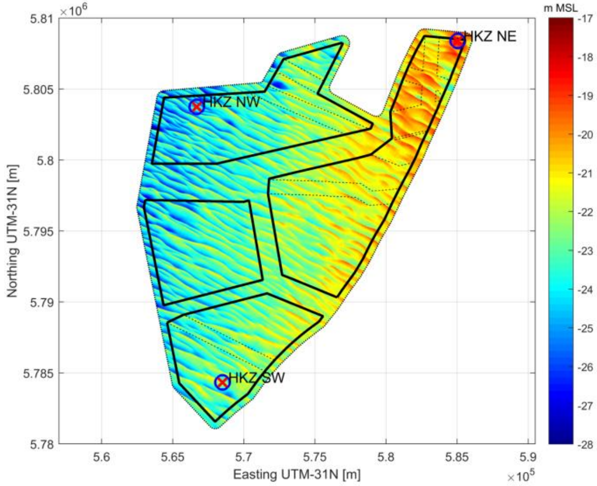
- Example of scour simulations with the Deltares' Scour Prediction Model for a monopile with a diameter of 8m, located in the NW of HKZ.

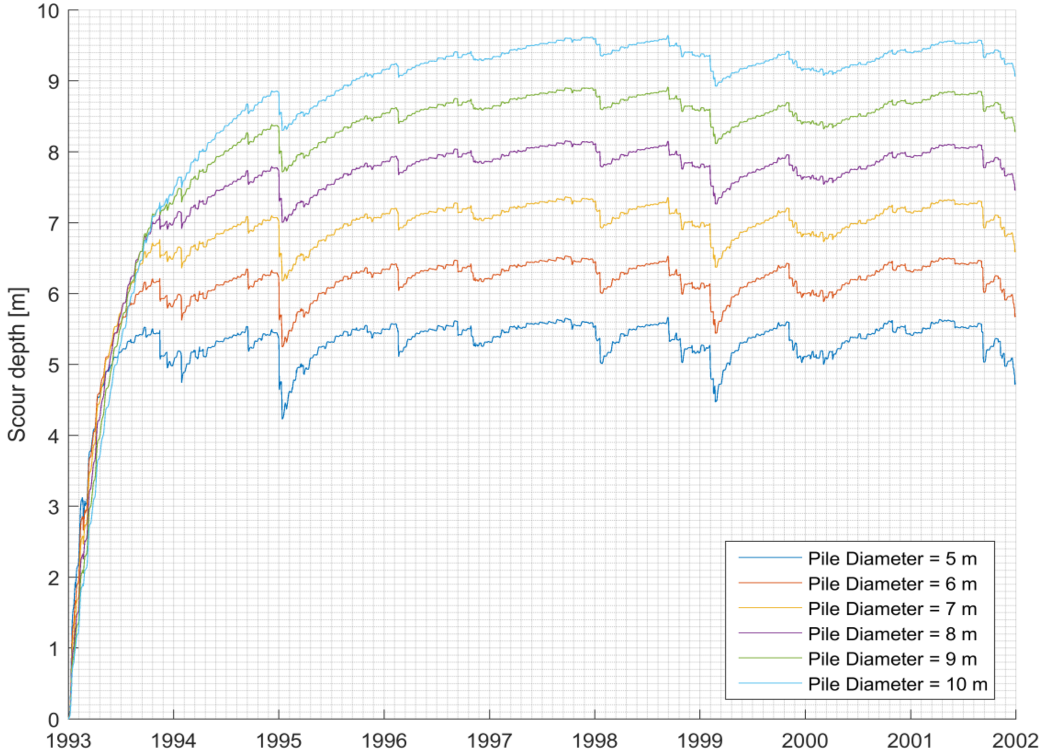




Scour predictions for HKZ

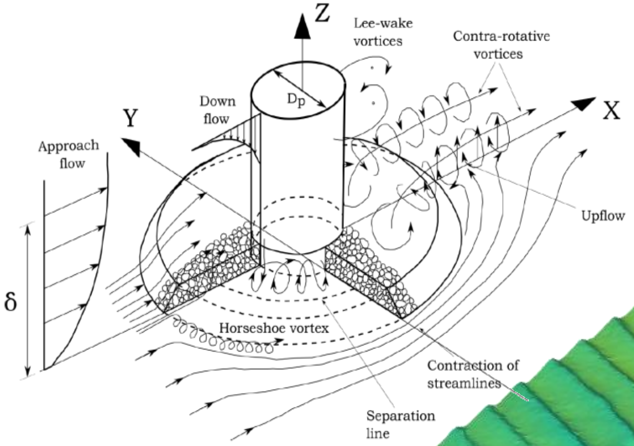
- Example of scour simulations with the Deltares' Scour Prediction Model for monopiles with diameters between 5 to 10m.

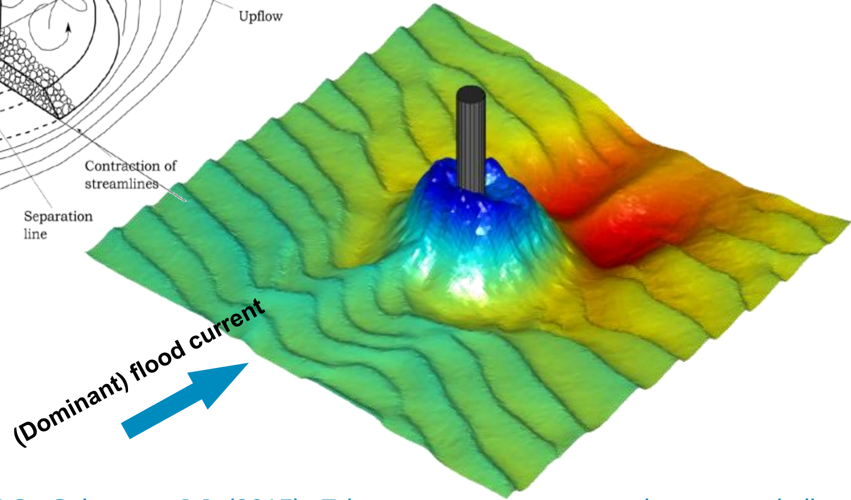




Edge scour development

- When a scour protection is installed (Strategy B), then in HKZ still scour will develop around the foundations: edge scour
- Edge scour occurs at slower time scales (order of years)
- Edge scour is mainly driven by the tidal current
- Location of deepest scour is governed by tidal asymmetry
- Depth is related to scour protection design (height above surrounding seabed, roughness and extent of scour protection

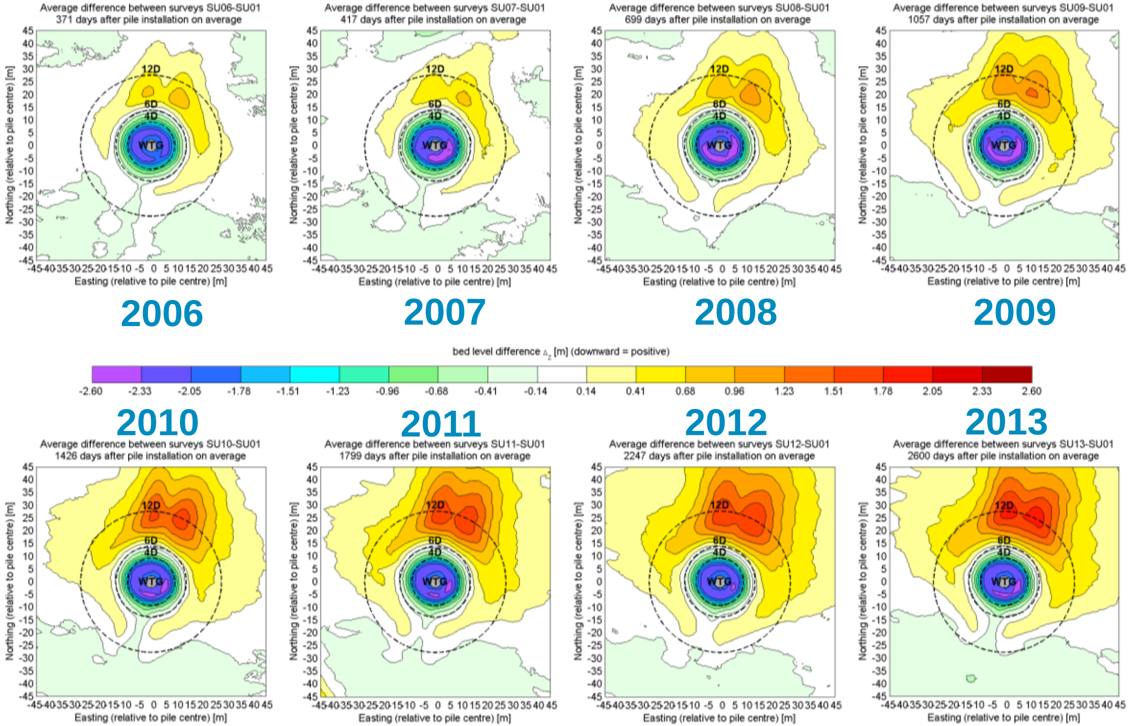




Petersen T.U., Sumer, B.M., Freds¢e, J., Raaijmakers, T.C., Schouten, J.J. (2015), *Edge scour at scour protections around piles in the marine environment - Laboratory and field investigation.* Coastal Engineering, Vol. 106, 2015, p. 42-72

Expected edge scour in HKZ

- Edge scour measurements in OWP Egmond aan Zee provide useful data for HKZ predictions
- For a double grading rock protection edge scour is estimated at: $S_{edge} \sim 1*h_{prot}$
- Deepest edge scour will occur in the NE-side of the foundation
- Edge scour can be mitigated by extending the filter layer: more falling apron material available
- Asymmetrical layouts can be considered to mitigate edge scour
- Think of favourable orientations for the cable connections



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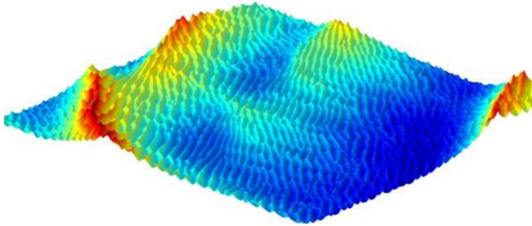

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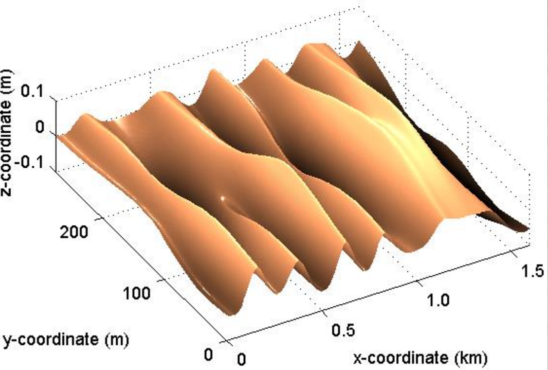
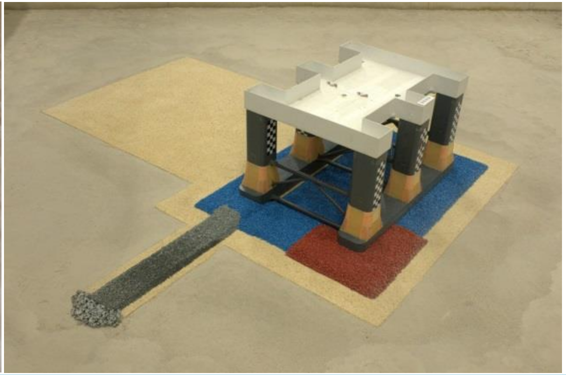
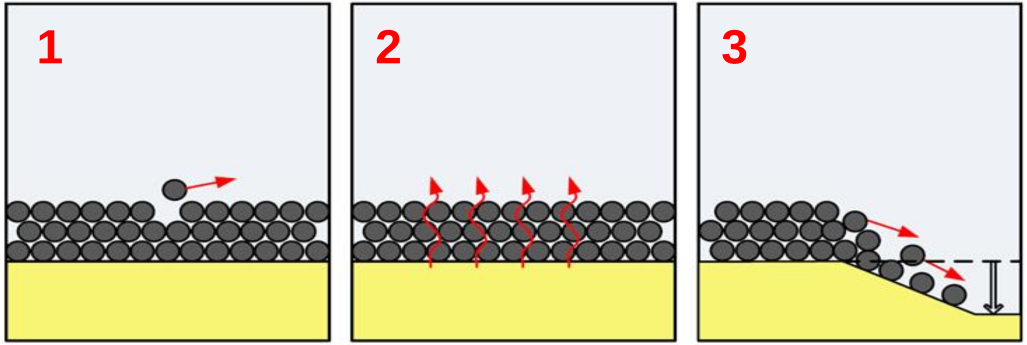




Requirements for a scour protection

Three main requirements:

1. External stability
2. Internal stability (filter function)
3. Flexibility (performance around edge scour and in morphodynamic areas)



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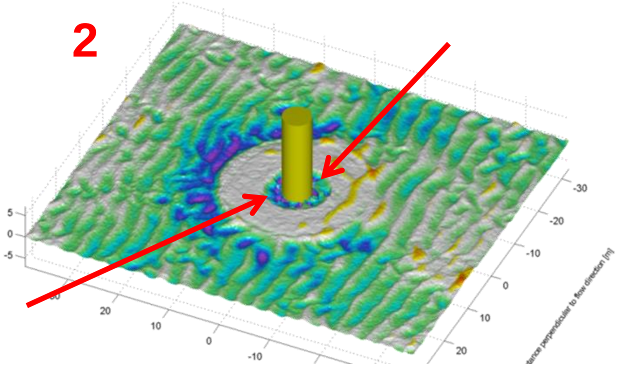

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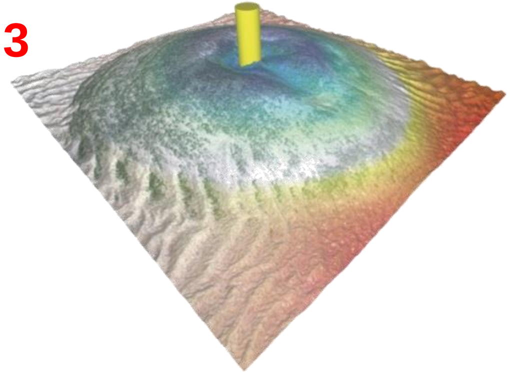
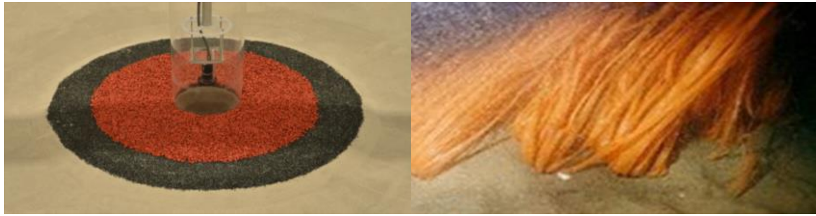
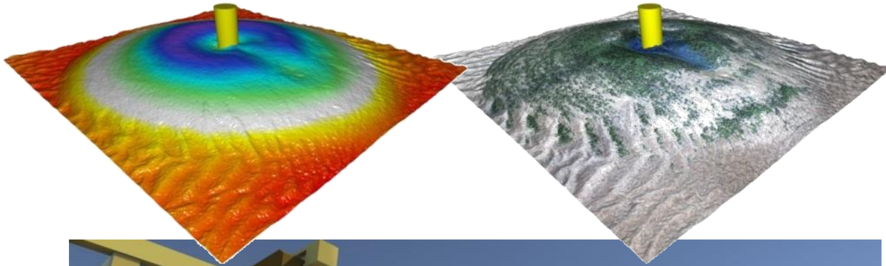


JIP HaSPro –Handbook Scour and Cable Protection Methods

- Scour and cable protection methods for offshore wind support structures and cables by model tests on 3 different model scales (from small to world's largest scale)
  - ✓ Optimizing conventional rock protection
  - ✓ Innovative protection systems
  - ✓ Nature-inclusive design
- Deriving design formulae and guidelines
- Drafting Handbook and Recommended Practice
- TKI-WOZ project: Sept. 2016 – Sept. 2019
- Funded by Participating companies and Netherlands Enterprise Agency; open for new participants



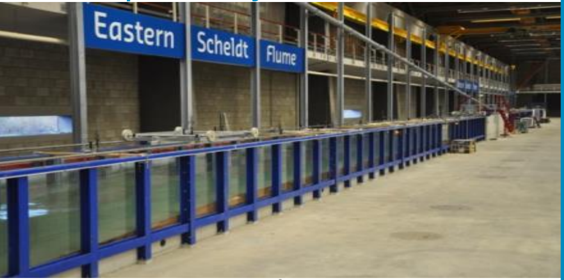


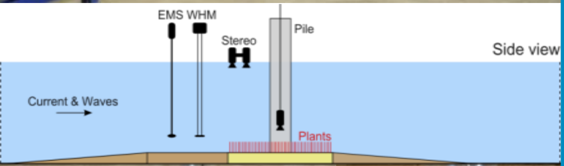
model test setup in Delta Flume

Overview of systematic scale model testing

Scheldt Flume

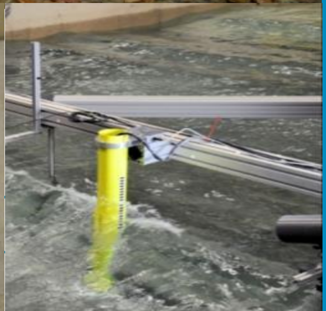
- Model scale 1:30 to 1:50
- Tidal currents + waves
- Fast cycle times: many exploratory tests





Atlantic Basin

- Model scale 1:20 to 1:40
- Tidal currents + waves
- Wide test section with mobile bed

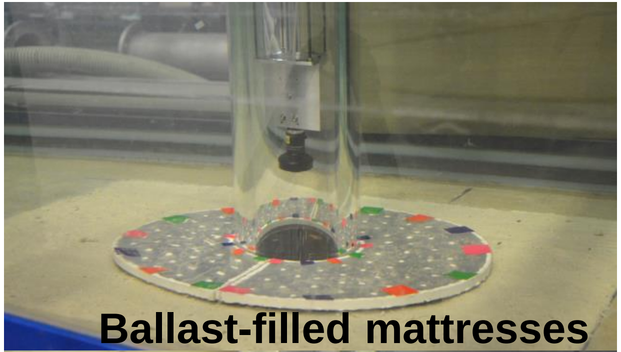


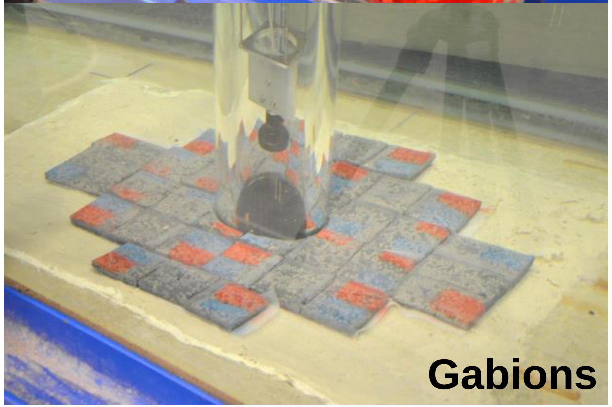
Delta Flume

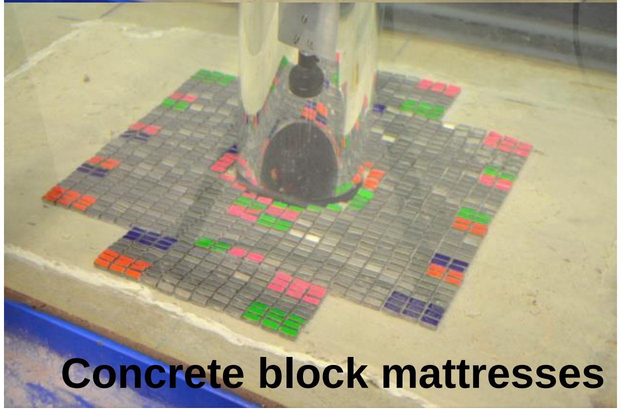
- Model scale 1:1 to 1:10
- World’s largest wave flume
- No scale effects

Some examples of innovative protections

Several alternatives for rock protections can be considered: examples of test setups to investigate failure mechanisms







Suitability matrix for scour protections in HKZ

Scour Protection Method	B_s	B_r	B_l	C_s	C_r	C_l
Static scour protection consisting of rock	+	+	-	--	--	--
Dynamic scour protection with two gradings of loose rock	++	++	+	-	-	-
Dynamic scour protection with a single grading of loose rock	+	+	+	+	+	+
Artificial vegetation	+	+	0	-	-	-
Concrete block mattresses	0	0	-	--	--	--
Gabions	0	0	-	--	--	--
Geotubes and Geocontainers	+	+	0	+	+	0
Rock-filled mesh bags	+	+	0	+	+	0
Ground Consolidators or Geohooks	0	0	0	+	+	0
Mattresses or rubber tyres	0	0	0	+	+	0

Scour Mitigation Strategies

B_S: Immediate scour protection, stable seabed

B_R: Immediate scour protection, rising seabed

B_L: Immediate scour protection, lowering seabed

C_S: Monitor & react, stable seabed

C_R: Monitor & react, rising seabed

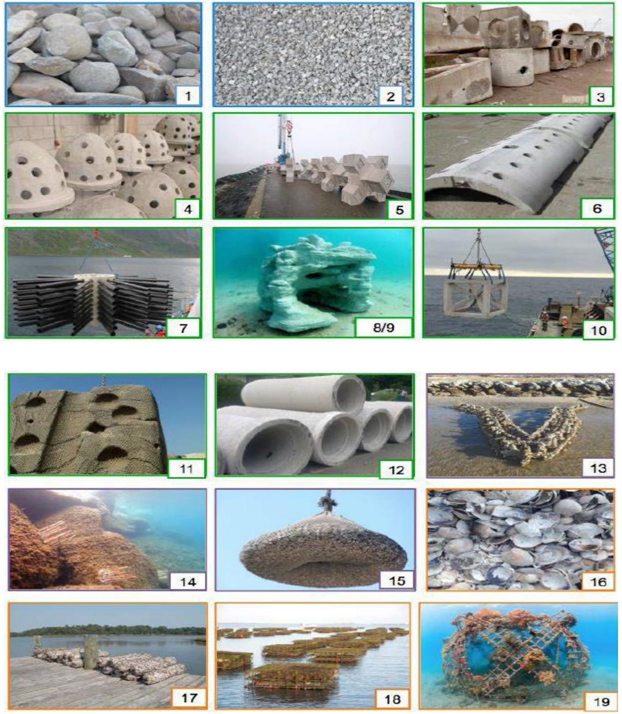
C_L: Monitor & react, lowering seabed

Nature-inclusive design / building with nature

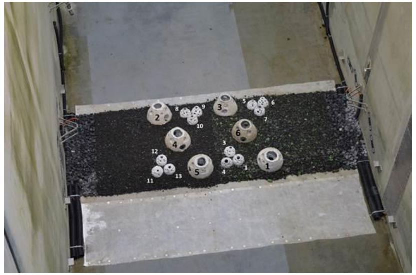
- With increasing land use of offshore wind farms and reducing LCoE, interest is increasing to enhance ecological value of wind farms and scour protection in particular
- Scour protections are already rich in ecology and show a great biodiversity (compared to the surrounding sandy seabed)
- Research on ways to further enhance the ecological quality of scour protections
- Focus on two umbrella species:
    1. Atlantic cod (*Godus morhua*)
    2. European flat oyster (Ostrella edulis)

Lengkeek, Wouter; Didderen, K.; Teunis, M.; Driessen, F.; Coolen, J.W.P.; Bos, O.G.; Vergouwen, S.A.; Raaijmakers, T.; Vries, M.B. de; Koningsveld, M. van (2017)

Nature-inclusive scour protection building



- Complex habitat yields diverse community
- Many shapes and materials can be considered
- Hydraulic aspects are currently being investigated in JIP HaSPro:
  1. stability of ecological concepts
  2. influence on surrounding protection



examples of tests of ecological concepts

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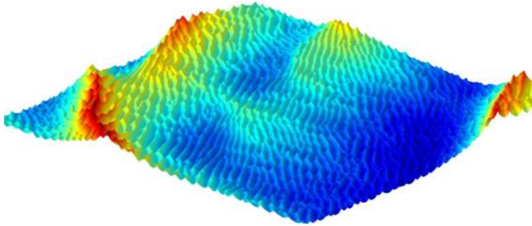
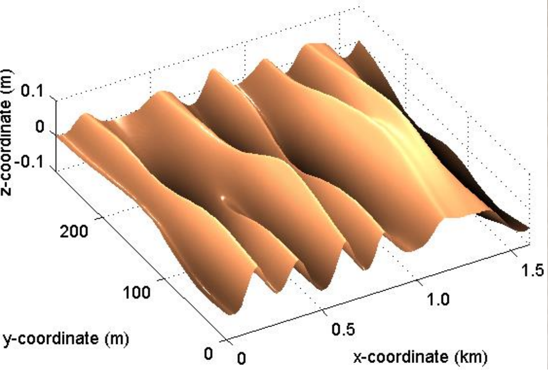
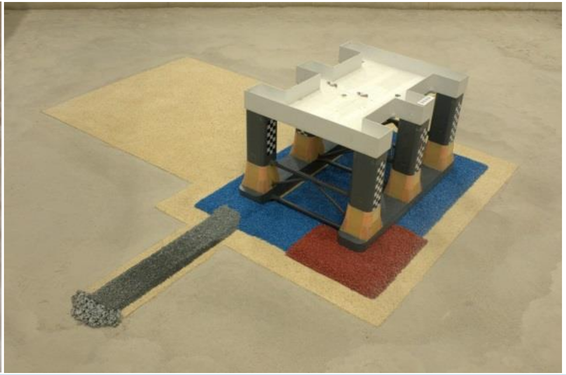
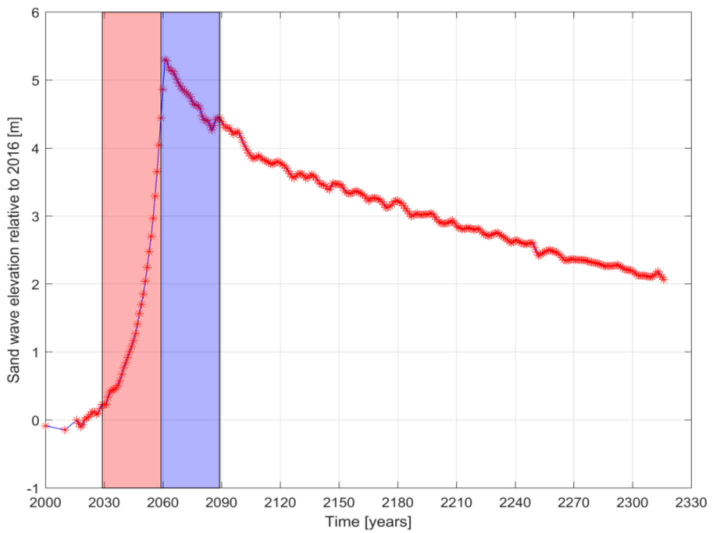






Example 1: Strategy A for piled jackets or monopiles

Selection of pile locations relative to a sand wave is of great importance and is a trade-off between accepted scour development and additional pile length



When the foundation is installed at this location in 2030, then this foundation will be installed in a sand wave trough and the seabed will rise approximately 4-5 m in 30 years

When the foundation is installed at this location in 2030, then this foundation will be installed just at the lee side of a sand wave crest and the seabed will first rise ~1m and then gradually lower to the initial seabed level

Example 1: Strategy A for piled jackets or monopiles

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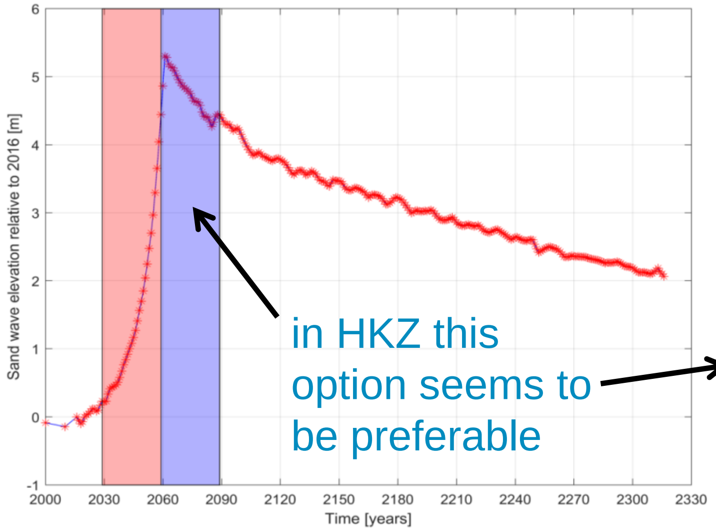


in HKZ this option seems to be preferable

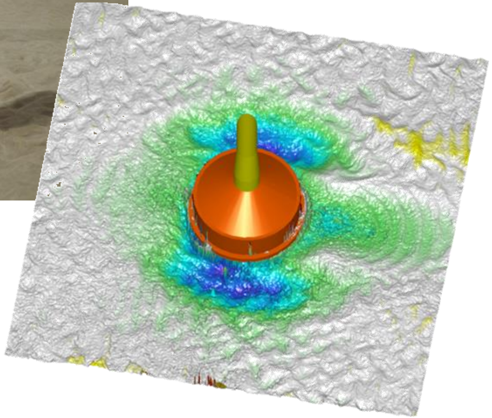
When the foundation is installed at this location in 2030, then this foundation will be installed in a sand wave trough and the seabed will rise approximately 4-5 m in 30 years

When the foundation is installed at this location in 2030, then this foundation will be installed just at the lee side of a sand wave crest and the seabed will first rise ~1m and then gradually lower to the initial seabed level

Example 2: Strategy B for Gravity Based Structures

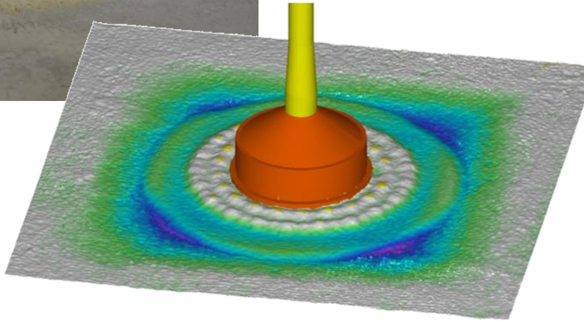
Strategies A and C are not feasible

GBS are prone to scour development and undermining in HKZ (mobile beds)



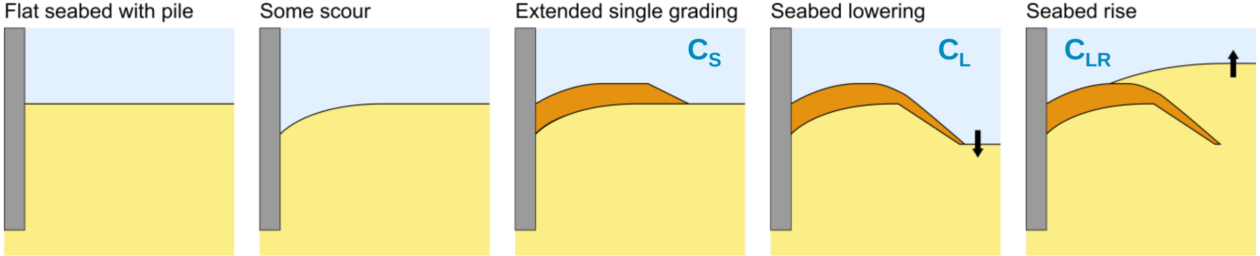
Strategy B is feasible

Often first the seabed is prepared, then a filter layer is installed and finally an armour is installed.

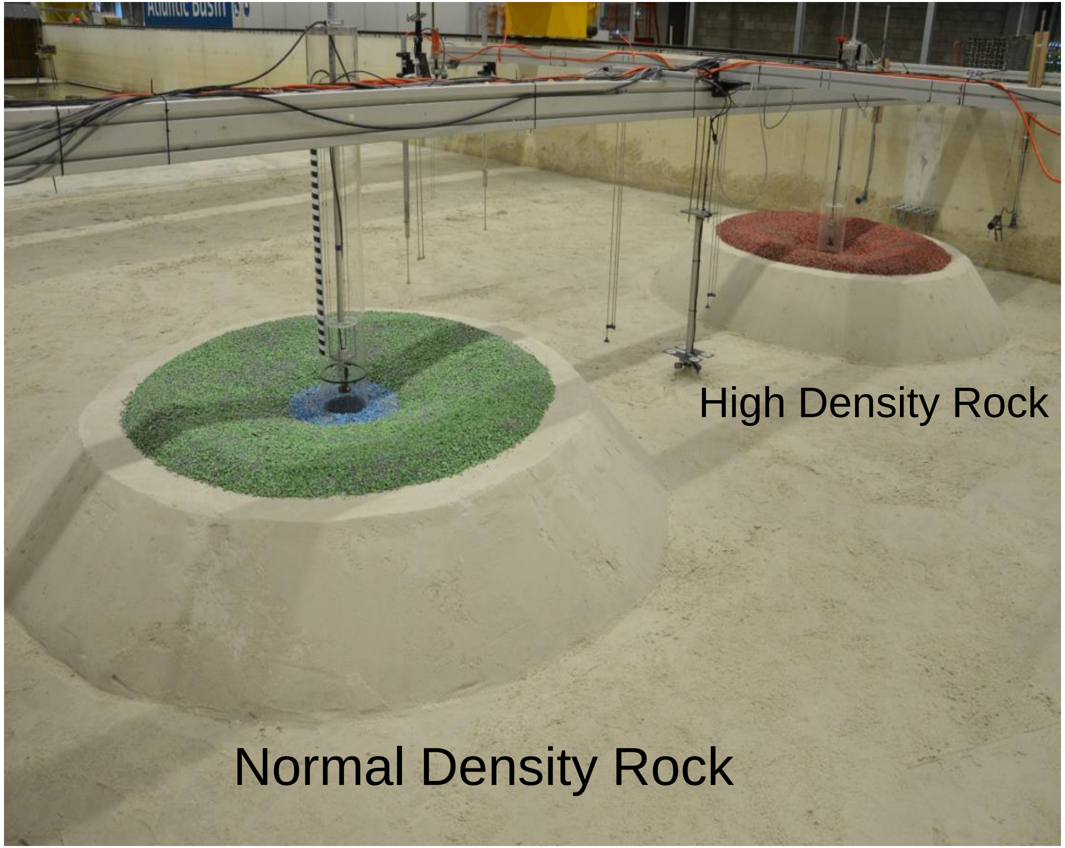


Example 3: Strategy C for monopiles

- Wind farm in morphodynamic area: migrating tidal flats and channels
- Integrated approach:
  - ✓ Determine relevant hydrodynamics
  - ✓ Predict seabed changes during lifetime
  - ✓ Predict scour development (now and for future bathymetries)
  - ✓ Develop scour mitigation strategies
  - ✓ Detailed design by physical model testing
  - ✓ Geotechnical lateral bearing capacity check to compare



Falling apron behaviour for extreme seabed lowering

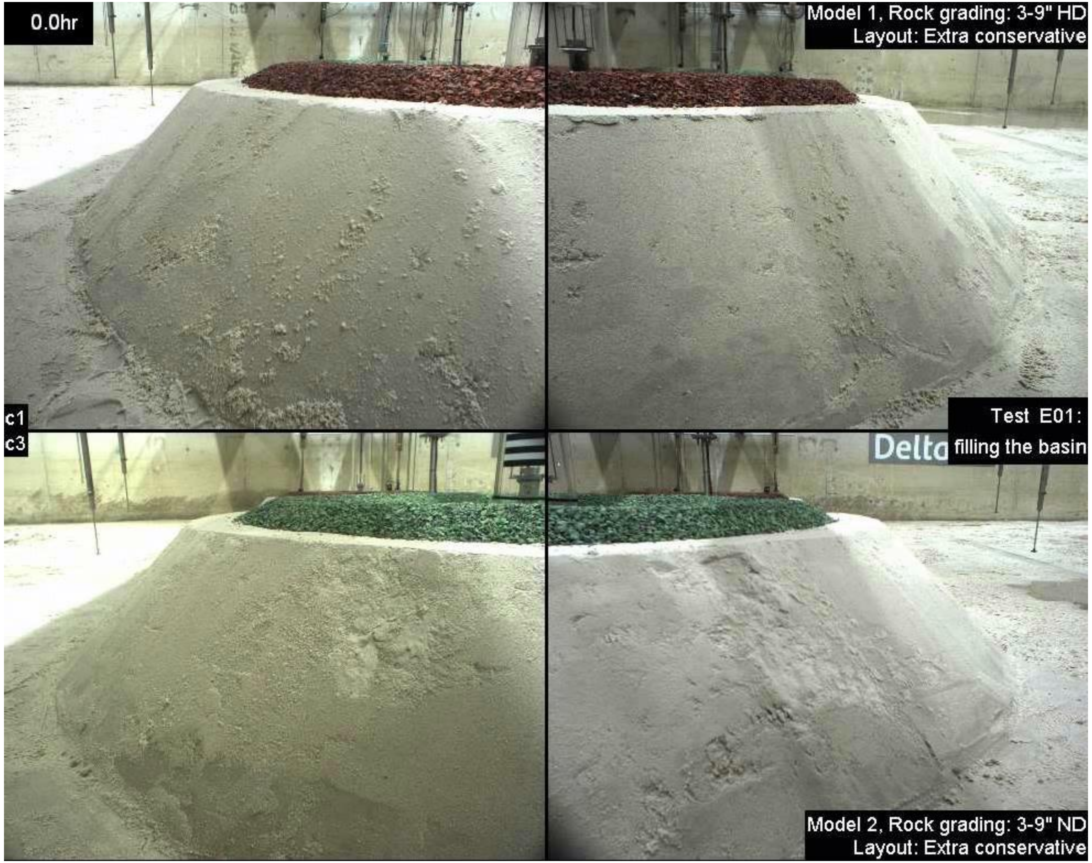


Two artificial islands with very steep slopes, that will be quickly eroded under tides, representing large-scale morphological development,

but in a fast-forward mode.

Deltares

Falling apron behaviour for extreme seabed lowering



Upper layout:

High Density Rock

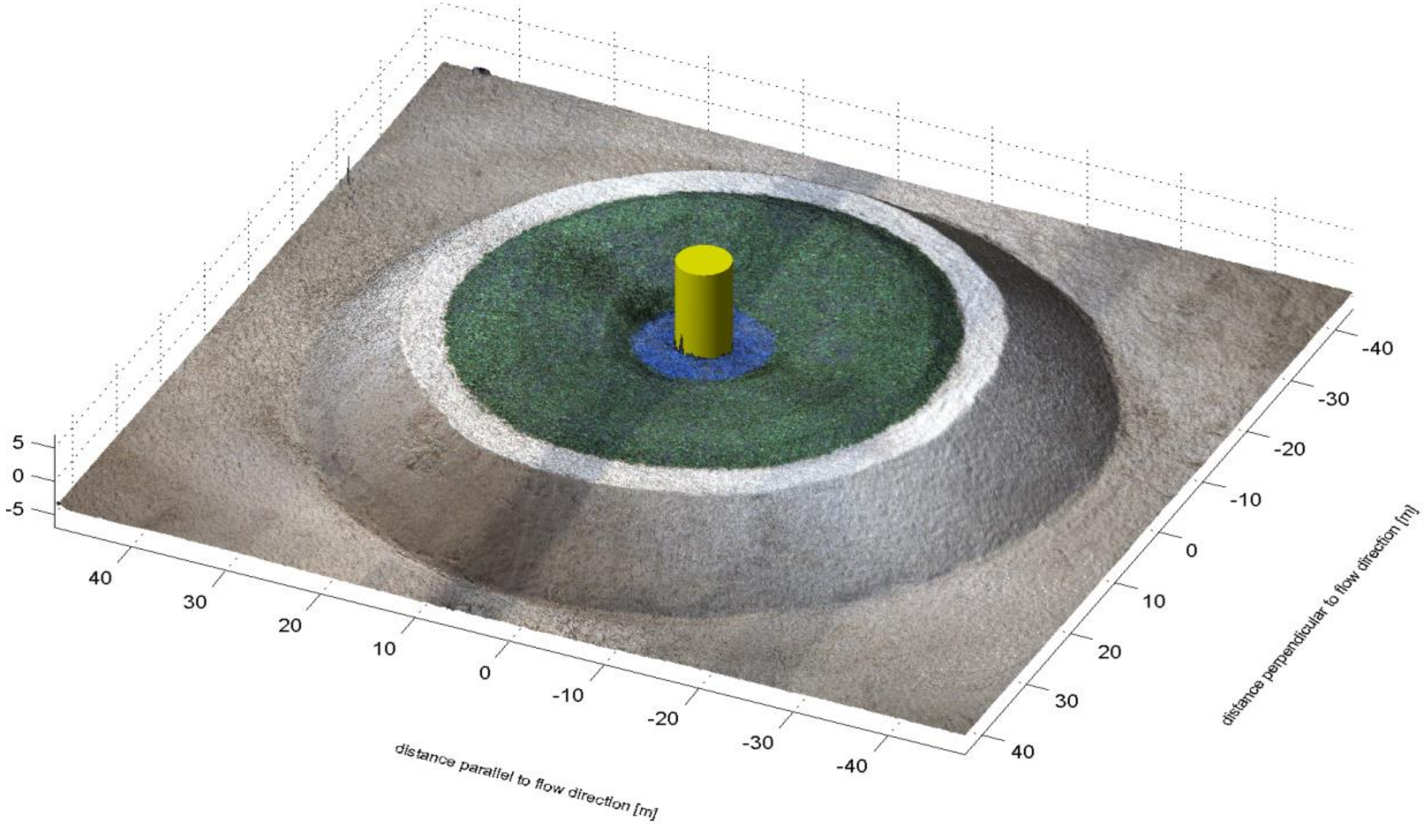
Movie illustrating how under several tidal conditions (flood and ebb currents) the morphological development (lowering seabed level) is modelled and how the scour protection will respond:

“falling apron behaviour”

Lower layout:

Normal Density Rock

Falling apron behaviour for extreme seabed lowering



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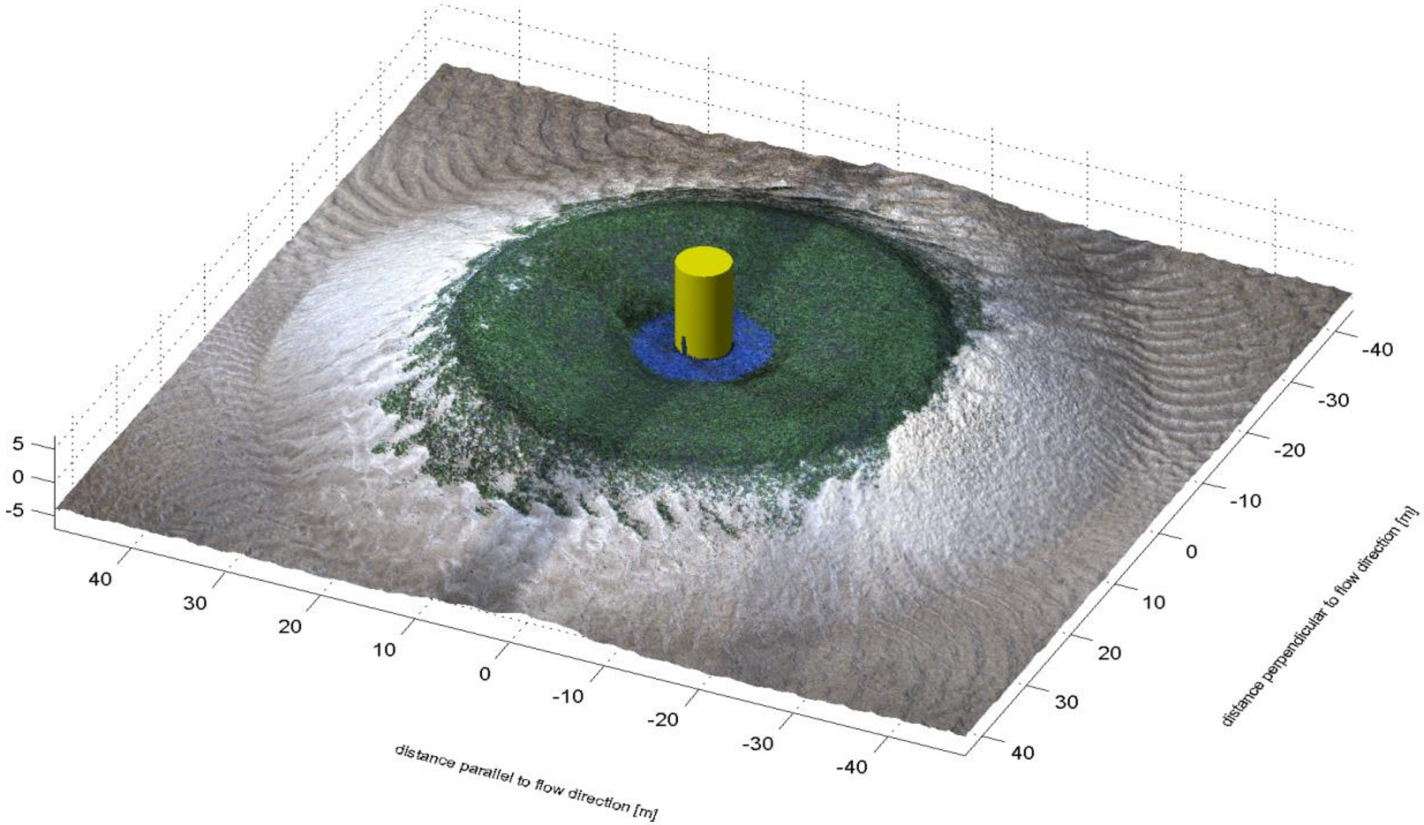
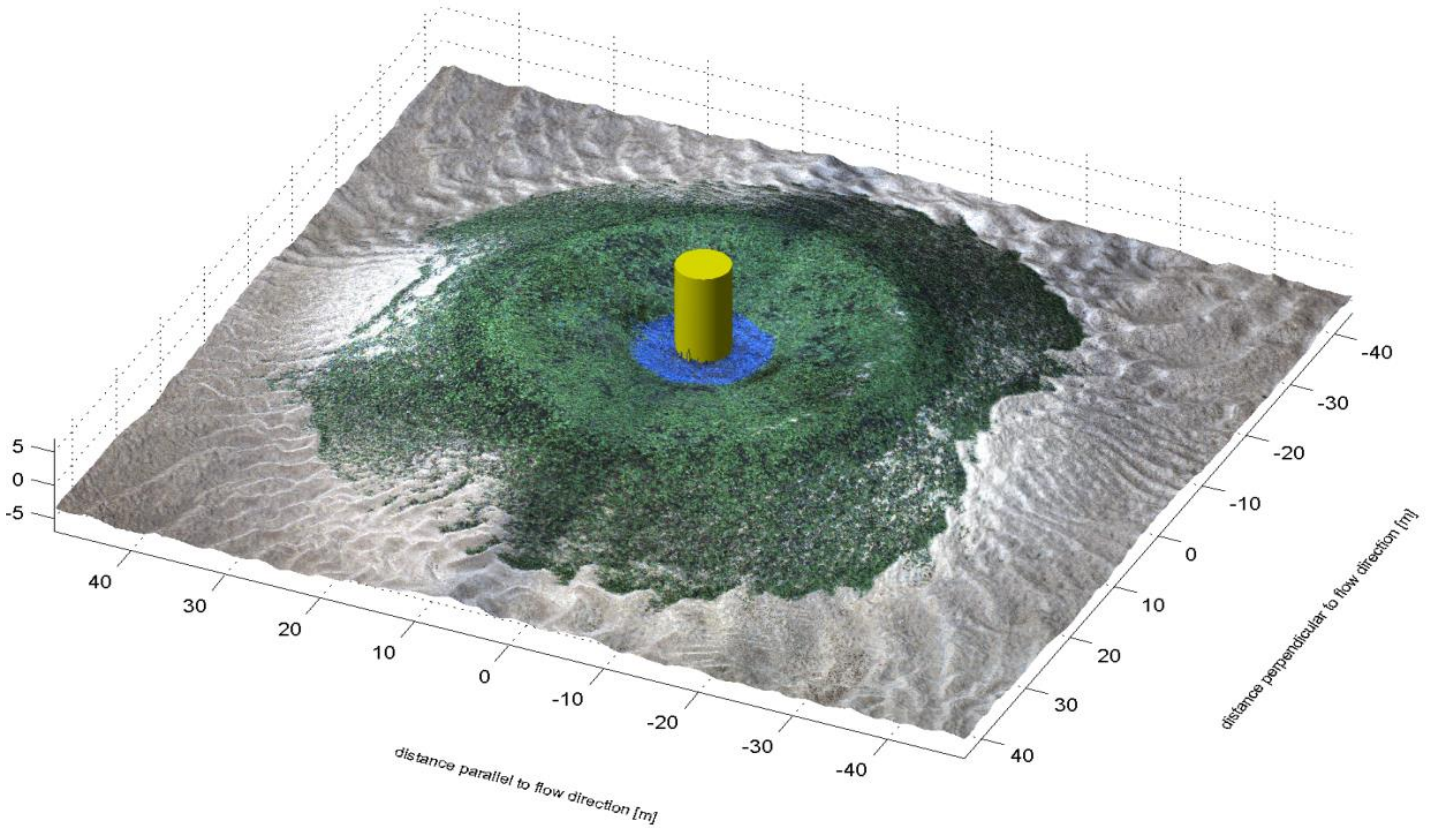


Falling apron behaviour for extreme seabed lowering



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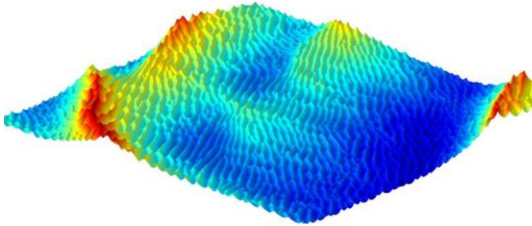
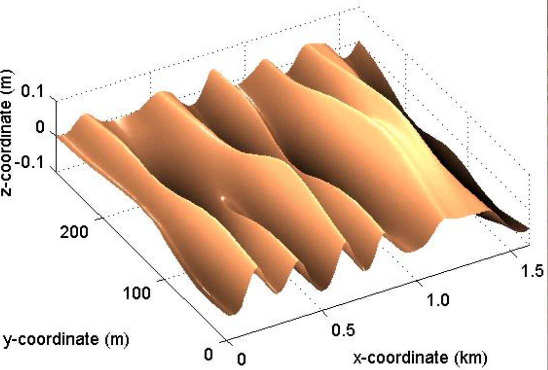
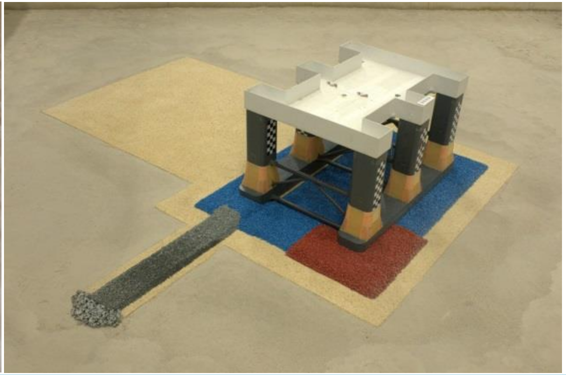
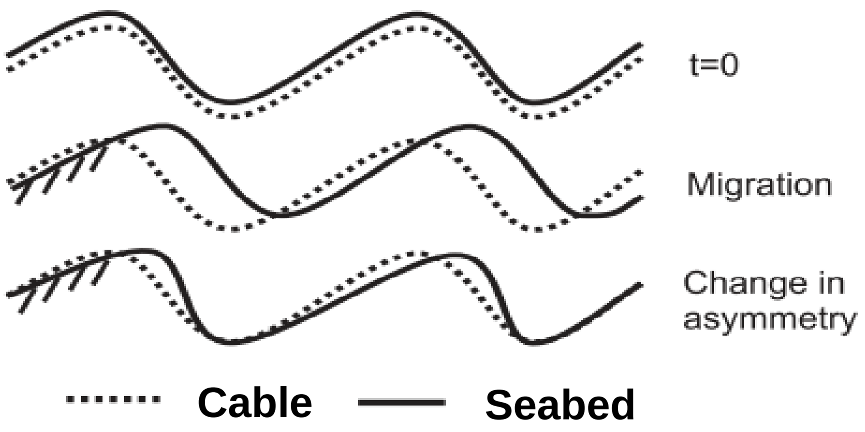






Cable routing - morphodynamics

- 70-80% of total value of insurance claims is related to cables
- Cable monitoring and repair require expensive marine operations
- Current methods to determine wind farm cable layouts are based on a flat, stable seabed



Roetert, T.J., Raaijmakers, T.C., & Borsje, B.W. (2017, June 25-30). *Cable route optimization for offshore wind farms in morphodynamic areas.* Paper presented at the The 27th International Ocean and Polar Engineering Conference, San Francisco, CA, USA.

Cable routing – flat bed optimization

Optimizing the cable routes under a flat seabed

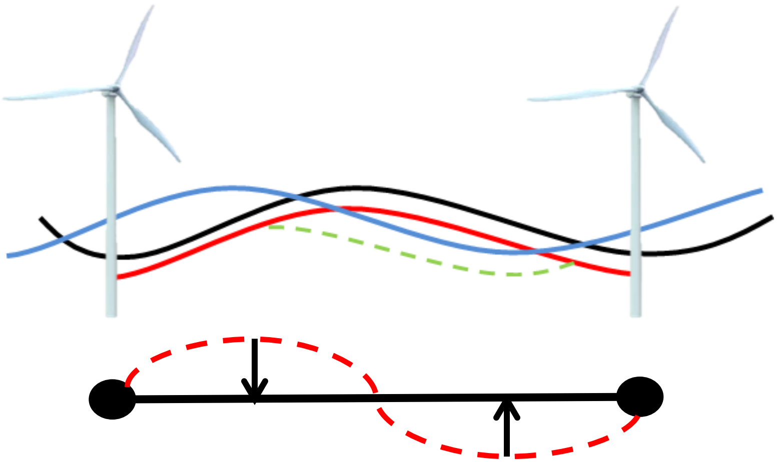
In a wind farm located far offshore, the turbines are often connected to one or more offshore high voltage stations (OHVS) via cable strings. Aim of the “overall” cable routing is to connect all these turbines to the OHVS, taking into account several routing constraints:

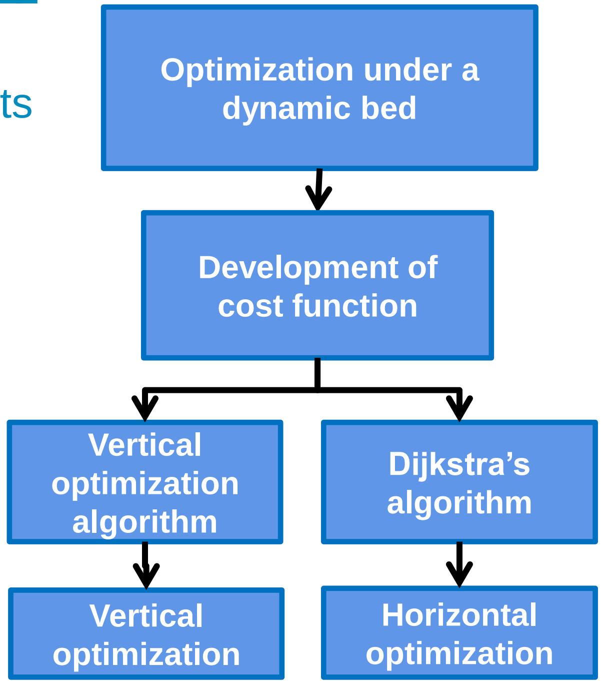
- Seabed remains flat/stable
- Cable capacity (e.g. 33 or 66 kV), which determines number of turbines per string
- Wind turbine capacity/yield
- Obstacles within the wind farm, e.g. pipelines, telecom cables and UXO’s are to be avoided
- Constraint of not crossing cables of the wind farm itself
- Locations with unfavourable geological characteristics are to be avoided

Cable routing – dynamic bed optimization

Optimizing the cable routes both horizontally and vertically

Taking into account seabed morphodynamics, effect on risks (e.g. anchors in case of limited burial depth) and potential costs related to failure and repair

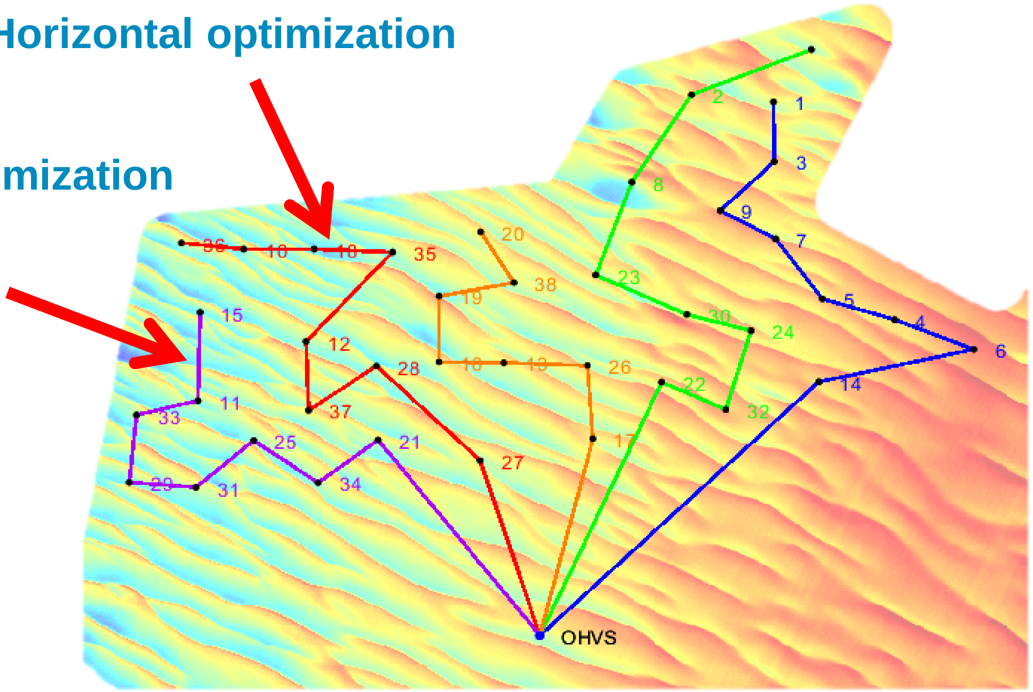




Dynamic bed optimization

Horizontal optimization

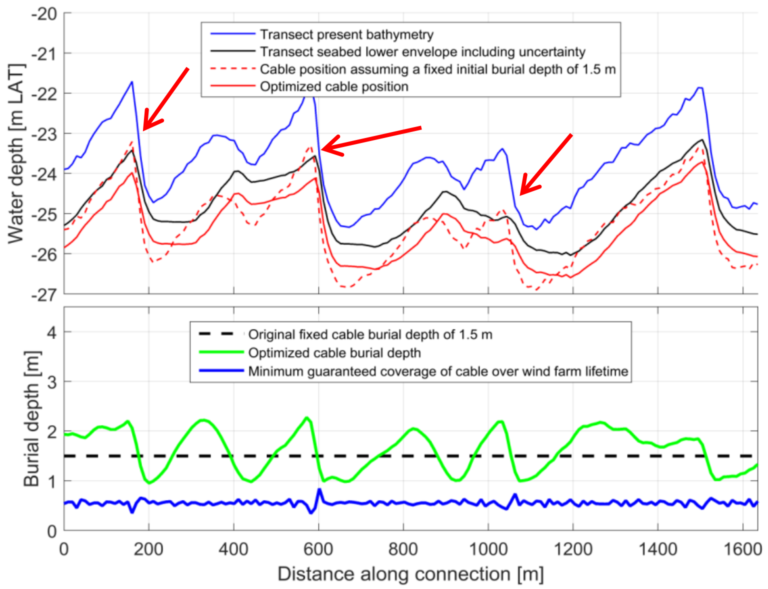
Vertical optimization



Vertical seabed optimization

Example: vertical micro-optimization of individual cable stretches

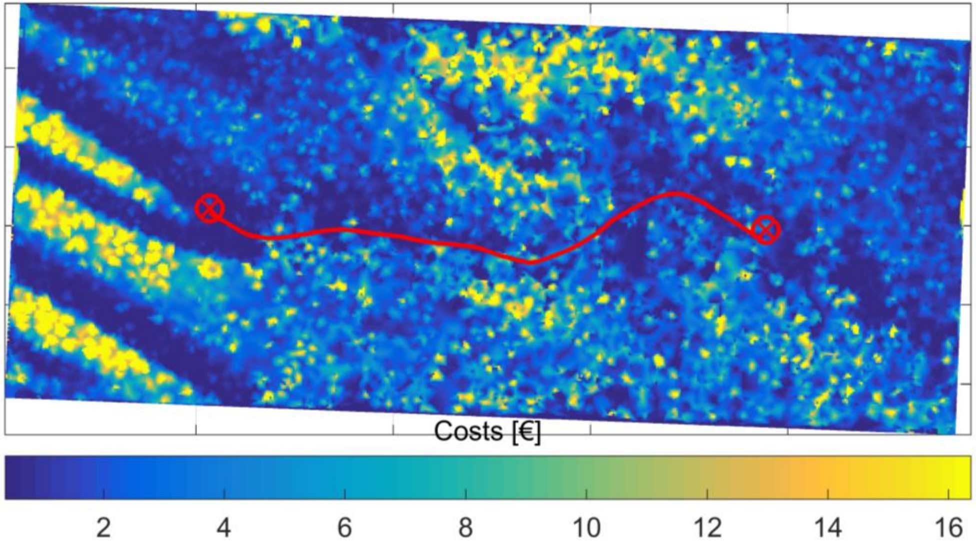
Optimization for dynamic seabed, buried deeper in areas experiencing severe seabed lowering



Horizontal seabed optimization

Example: horizontal micro-optimization of individual cable stretch using Dijkstra's shortest path algorithm

Optimization for dynamic seabed, avoiding areas with high costs keeping initial burial depth fixed at 1.5m



Key take-aways

Deltares

Three scour mitigation strategies can be considered:

A. free scour development (and adjust structural design)
B. immediate scour protection
C. monitor and react (only if necessary or intended)

in combination with the morphodynamics at the location of the foundations:

S. stable seabed (less than 1m autonomous seabed change)
L. lowering seabed
R. rising seabed

and the selected structure type, of which the following were addressed:

- ✓ Monopiles
- ✓ Gravity Based Structures
- ✓ Piled Jackets
- ✓ Suction Bucket Jackets
- ✓ Jackup vessels (for temporary operations)
- ✓ Cables

Many combinations are feasible, when designed properly!

more information?

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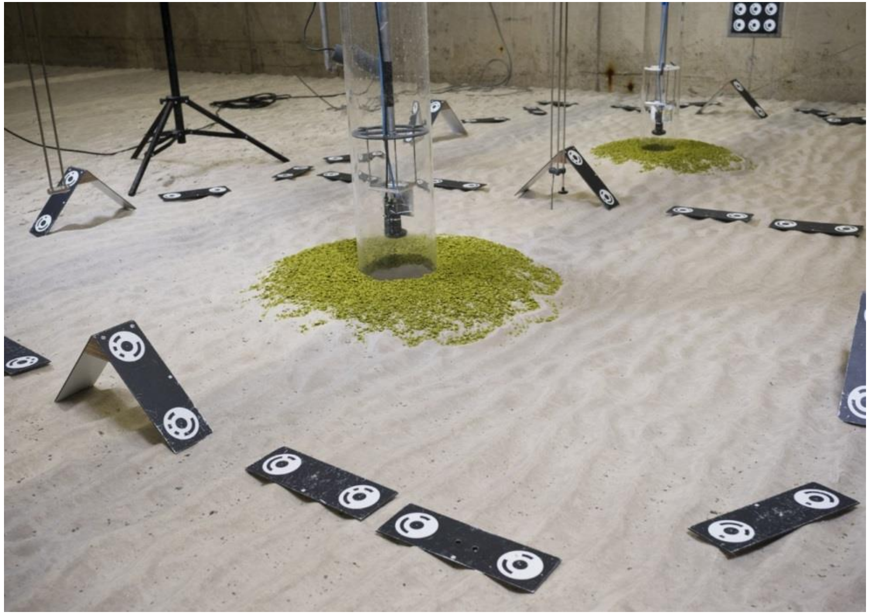
Closing

- Questionnaire
- Lessons learned
- Availability panel
- Communications
  - http://offshorewind.rvo.nl
  - woz@rvo.nl



Thank you very much!