An overview and conclusion concerning the use of Bruce anchors to anchor crab-pot-strings in Prinses Amalia Offshore Windpark

Summarising report

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Summary

This report serves both as i) the final report for the cooperation agreement between the Dutch government, Eneco and the consortium Win-Wind for an experiment on fisheries with pots (gear code FPO) in the operational offshore Prinses Amalia Windpark and ii) the wrap up and review of results for Project no. BO-43-119.01-028 Add Ankermobilisatie krabben and reflects on results of the project Win-Wind.

Introduction

Fishing, working and manoeuvring within Offshore Windfarms is very different from regular fishing activities on the open North Sea. For passive fisheries with crab-pot-strings in Prinses Amalia Windpark cooperation with and from the windfarm operator Eneco had to be achieved. In risk evaluation sessions it was determined that crab-pot-strings must be provided with dahns (buoys with flagsticks) in accordance with legal provisions. When using chains to fixate crab-pot-strings with dahns to the seabed, they become mobile with e.g. high water levels, currents and winds. Mobilised crab-pot-strings might get caught in the infield electricity cables and subsequently damage them. Due to this risk, Eneco withheld permission for the use of strings with dahns, anchored by chains in Prinses Amalia Windpark.

Several studies have been performed ranging from damage tests, mobilisations tests with chains to fixate crab-pot-strings to the seabed, several Bruce anchors with different modifications to prevent hooking into infield electricity cables (reducing risk: both chance and damage), tests with default Bruce anchors to assess the damage these might inflict and also tests to assess the chance crab-pot-strings can be mobilised under different weather and current conditions.

This letter report provides a wrap-up, overview and conclusion of all these studies on the risks of using Bruce anchors in Prinses Amalia Windpark. It includes also a concise description of the process that led up to this approach.

Results

Dahns with chains instead of anchors

It appeared that the combination of crab-pot-strings with dahns and chains is an unstable setup. At maximal extra water level of 121cm and higher as compared to Normaal Amsterdams Peil, crab-pot-strings with dahns were mobilised whereas strings with polyform buoys and chains were not mobilised under conditions up to 1.84m maximal water level as compared to Normaal Amsterdams Peil. Applying the haul-out indicator ($Indicator_{Haul-out}$ see below), strings with dahns and chains were mobilised starting at 176 cm $Indicator_{Haul-out}$ whereas strings with polyform buoys and chains were not mobilised up to 581 cm $Indicator_{Haul-out}$. Concluding, chains are not suitable to secure crab-pot-strings with dahns to the seabed.

Modified Bruce anchors with adaptations to prevent the hook in

Modified anchors with adaptations to prevent the hook in of anchors into an infield electricity cable were tested. The modifications helped in preventing the hooking in of the Bruce anchors infield electricity cable but also prevented the digging in of those anchors into the sand. Concluding the modified Bruce anchors do not function with anchor crab-pot-strings with dahns to the seabed.

Damage tests with Bruce anchors to the infield electricity cable

In a beach experiment, Bruce anchors were pulled against an infield electricity cable. When applying the same force as water currents can maximally exert, only superficial 2-dimensional damage was inflicted to the infield electricity cable. When about twice as much force was applied, small, deeper (3-dimensional) holes were generated by the Bruce anchor. This happened where the flukes[1] of the Bruce anchor penetrated the outer protection layer. The raffia layer and the outer bitumen layer were

[1] Fluke: broad triangular plate on the arm of an anchor.

damaged, but the galvanized steel wire protection was not visible in any case. Concluding, the damage a Bruce anchor can inflict is **Negligible**, the lowest category of damage in the risk systematics.

Mobilisation tests of normal Bruce anchors
In order to test the chance element of Risk the mobilisation of crab-pot-strings with dahns and 10 kg Bruce anchors was tested under summer conditions in the coastal zone of the North Sea near Scheveningen. During periods of 7 and once 8 Bft (18 m/s) winds, the crab-pot-strings were not mobilised. Only once one Bruce Anchor had slipped and the dahn moved but that was because the Bruce anchor had entangled itself in its own rope preventing fixation in the seabed. Concluding, the chance of crab-pot-strings with dahns and 10 kg Bruce anchors being mobilised under conditions of 18 m/s **may never occur** (the lowest category of chance in the risk systematics.)

The risk of using Bruce anchors is with these two lowest aspects also the lowest possible.

$\text{Indicator}_{\text{Haul-out}}$
Crab-pot-strings with dahns and Bruce anchors have to be taken out once sea conditions get too adverse. But what exactly is considered too adverse? The potential mobilisation of crab-pot-strings with dahns and Bruce anchors is a complex process not easily captured in a single indicator like wind force. An indicator was developed here on the base of the mechanisms of mobilisation (currents and waves hauling on the dahn). The $\text{Indicator}_{\text{Haul-out}}$ was assembled based on Maximum extra Water Level as compared to Normaal Amsterdams Peil, Swell and Average Wave Height over 10 min periods.

A threshold of the $\text{Indicator}_{\text{Haul-out}}$ was defined for haul-out. When based on the predictions at Hoek van Holland and Eurogeul 13 an $\text{Indicator}_{\text{Haul-out}}$ will be predicted of **445 cm.** The crab-pot-strings will be hauled out before this value will occur. Wageningen Marine Research calculated this value during the entire experiment in PAWP. As an extra safeguard, two fishermen also observed the weather and sea condition predictions and would give a warning when they have the impression sea condition gets too adverse for safe deployment of the strings. In both cases the project leader of Wageningen Marine Research will open a dialogue with the project leader of Eneco on how to act. The project leader of Eneco has the final decision on the obligation for haul-out.

Conclusion
The risk of deploying crab-pot-strings with dahns was investigated under different setups. Crab-pot-strings with dahns and 10 kg Bruce anchors pose the lowest Risk possible. As an extra risk mitigation, it is agreed to take out the crab-pot-strings from Prinses Amalia windpark when sea conditions get too adverse. Thereto an $\text{Indicator}_{\text{Haul-out}}$ was defined with a threshold. In this case, based on predictions, the Eneco project leader will decide whether the crab-pot-strings need to be hauled out Prinses Amalia windpark.

1 Introduction

With the rapid upscaling of offshore wind farms (OWFs) on the North Sea, pressures are mounting on e.g. nature and fisheries. Successful development and exploitation of OWFs requires integration in the environment, in terms of ecology and in relation to other users. Multi-use and nature inclusive design are used to meet these wishes and needs.

Passive crab-pot-fisheries (gear code FPO) is considered to be a viable option of multi-use in OWF's. To enable this form of multi-use, several research projects are conducted like the TKI financed Win-Wind project. In Win-Wind a collaboration was established between the Government of the Netherlands, Eneco and the consortium Win-Wind to perform crab-pot-fisheries in Prinses Amalia Wind Park (PAWP). Part of this collaboration agreement was a work method statement (WMS, Rozemeijer et al., 2020). In this WMS the outline, structure and implementation of the proposed experiment were determined, dealing with the risks associated to working in an industrial environment with high voltage and in a dynamic, harsh and unpredictable environment such as the North Sea. A major issue was the fixation of crab-pot-strings to the sea bed. Several studies have been performed. This report is a synthesis of the results.

1.1 Setting

This report serves both as i) the final report for the cooperation agreement between the Government of the Netherlands, Eneco and the consortium Win-Wind for an experiment on passive crab and lobster fisheries with pots (gear code FPO) in the operational Prinses Amalia Windpark (PAWP, Figure **1**) and ii) the wrap up and review of results for Project no. BO-43-119.01-028 'Add Ankermobilisatie krabben'. The experiment on crab and lobster fisheries with pots in PAWP will take place in the spring and summer of 2023. Hence the anticipated results are not integrated yet. This report is a report on risk mitigation in order to safely carry out the experiment in PAWP. In offshore wind farm (OWF) Borssele II experimental fisheries on crab have taken place but the results are not analysed yet.

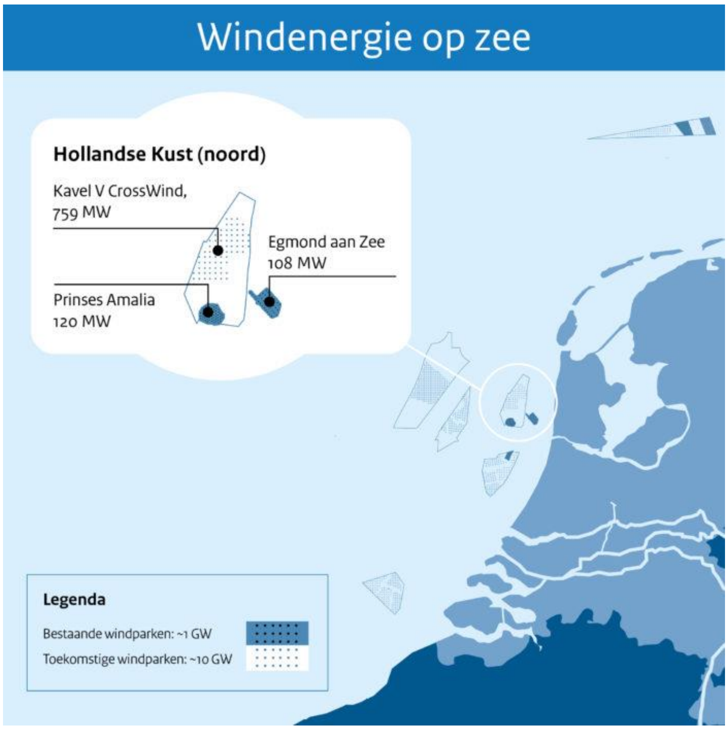


Figure 1 the position of Prinses Amalia Windpark along the Dutch coastline. It is integrated in the concession area of Hollandse Kust Noord.

1.2 Context

In 2019, the project Win-Wind was granted permission to conduct an experiment with crab-pot-strings on European lobster (*Homarus gammarus*) and brown crab (*Cancer pagurus*) in (PAWP). Following this permission, a cooperation agreement was drawn up between the Government of the Netherlands, Eneco and the consortium Win-Wind. Part of this collaboration agreement was a work method statement (WMS, Rozemeijer et al., 2020) in which the outline, structure and implementation of the proposed experiment were determined. During risk evaluation sessions it appeared that there were serious doubts about the anchoring performance of crab-pot-strings, both regarding the strength of grip in the bottom and regarding the risk of hooking into and damaging an infield electricity cable.

An initial study of anchoring behaviour of crab-pot-strings with dahns anchored by chains (Figure 2, Figure 3) showed a high mobility of the crab-pot-strings, and the risk of getting caught in the infield electricity cables (an unacceptable risk for Eneco). This was most likely caused by the dahns, which are more susceptible to currents than e.g. the polyform A1 buoys (fenders, Figure 4) (Korving et al., 2021, Rozemeijer et al., 2022a). NB dahns are legally obligatory with regards to national and European fisheries legislation (EU 2005, Article 12: EU 2011, Article 15).

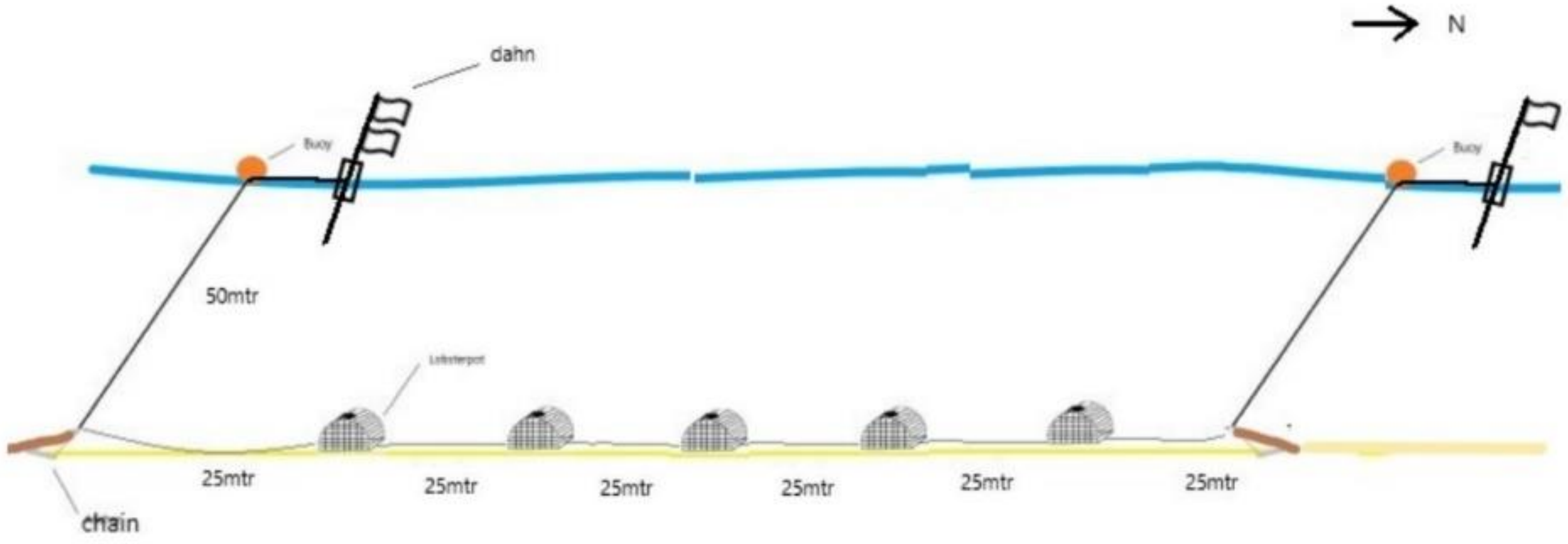


Figure 2 Crab-pot-strings with five pots and two chains. A dahn is attached (buoy with flag(s), counterweight, flashlight and radar reflector) next to the buoy. The double flag means the most southern buoy of the string. A single flag signs the most northern buoy. In this set up mutual distance between the pots is 25m. This distance is depending on depth and is at least 2 times the local water depth.

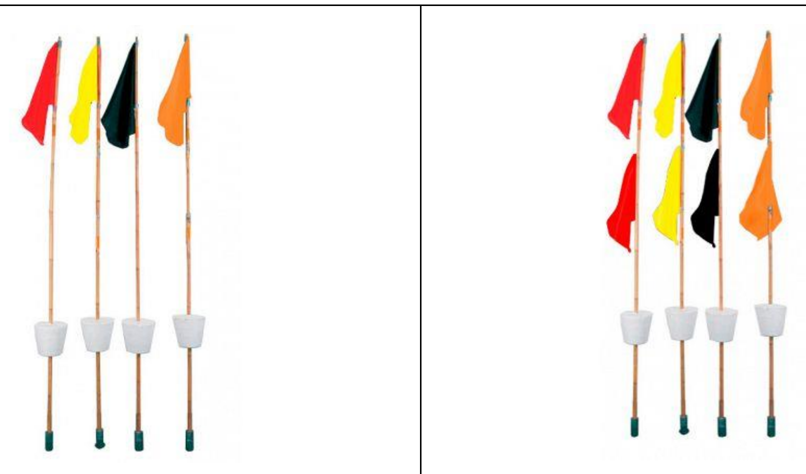


Figure 3 North dahn (one black flag) and the South dahn (two black flags) on a bamboo stick of 4.2 m, with float and counterweight of 2 kg. Danhs are equipped with flashlight and radar reflector.

Figure 4 Polyform A1 buoy, buoyancy 7.8-13 kg, weight: 1.15 kg. Length: 38.0 cm. Diameter 29.5 cm.

As an alternative to chains, modified Bruce anchors were suggested. However, a follow-up study with modified Bruce anchors showed that these anchors did not hook in the infield electricity cable but also negatively influenced the burial behaviour (Rozemeijer et al., 2021a).

The risk (

Equation 1) of using anchors in PAWP had to be assessed to continue the development of the experiment on crab and lobster fisheries with pots in PAWP. A third study (Rozemeijer et al., 2021b), in which original Bruce anchors were tested for mobility near three shipwrecks (the chance part c), showed that Bruce anchors are not mobilised under wind force 8 Bft (18 m/s). In a fourth study into the damage that can occur if a Bruce anchor gets caught behind an infield electricity cable (Figure 6), showed that forces comparable to the most extreme pulling force of the North Sea the Bruce anchor only affects the outer sheath of the infield electricity cable (Rozemeijer et al., 2022b).

Equation 1

Risk = chance*damage: R = c*D

(From International Maritime Organisation, 2018, see also Annex 1).

1.3 Assignment

Several studies have been performed ranging from damage tests, mobilisations tests with chains to fixate to the seabed, modified versions of Bruce anchors to prevent hooking into infield-electricity-cables (reducing risk: both chance and damage), tests with standard Bruce anchors to assess the damage these Bruce anchors can inflict and also tests to assess the chance crab-pot-strings can be mobilised under different weather and current conditions.

This report provides a wrap-up, overview and conclusion of all these studies on the risks of using Bruce anchors in PAWP. It also includes a concise description of the process that led up to the studies mentioned above.

1.4 Reading guide

In chapter 2 the studies are introduced that have been used for this report. In chapter 3 the results of the different studies are summarised (with a concise summary on the materials and methods used). In chapter 4 the results are discussed, conclusions are drawn and suggestions for further research and implementations are given.

2 Used studies and reports

The following studies and reports were integrated in this overview. They each served as part of the total approach.

Table 1 overview of the used studies and reports for this review. Prinses Amalia Windpark (PAWP)

Considering	Reference	Content
Work Method Statement PAWP	Rozemeijer M.J.C., A. Korving, J. Don, W. Zaalmink (2020) Work Method Statement Project Win-Wind to catch brown crab and lobster in Princess Amalia Offshore Wind Park. Wageningen Marine Research report C028/20, CONFIDENTIAL.	This report defined the initial risks and *modus operandi* for working with crab-pot-strings in PAWP. Applying the WMS should lead to a permit to access for PAWP.
String stability	Korving A., R. Cramer, M.J.C. Rozemeijer (2021). Memo String mobilisatie onder verschillende condities. Aanvullende bijlage voor Work Method Statement van TKI project Win-Wind met maatgevende weerscondities. Date: 13-08-2021.	In this and the following report the stability of the crab-pot-strings when using dahns and chains under natural sea conditions was determined. It appeared that the crab-pot-strings with dahns and chains were moved over distances and crab-pot-strings with fenders remained stable on their position.
String stability	Rozemeijer M.J.C., Korving A., R. Cramer, (2022a). String mobilisatie onder verschillende condities. Wageningen Marine Research Briefrapportage Aanvullende bijlage voor Work Method Statement van TKI project Win-Wind met maatgevende weerscondities. Date: Wageningen Marine Research Rapport C029/22, https://doi.org/10.18174/571398	Stability of the crab-pot-strings when using dahns and chains.
Testing modified Bruce anchors	Rozemeijer M.J.C, R. Cramer, A. Korving, C. Meeldijk (2021a). Het testen van aangepaste Bruce ankers op hun geschiktheid voor het gebruik in Offshore Windmolenparken. Wageningen Marine Research Briefrapportage KD-2021-018_Alternatieve ankers in windparken op zee BO-43-119.01-012XXX.	Modified Bruce anchors were tested on the risk of hooking into an infield electricity cable. They did not but the modifications that prevented this also reduced burial behaviour thereby making modified Bruce anchors unsuitable for anchoring.
Assessing damage of Bruce anchor	Rozemeijer M.J.C., Korving A., R. Cramer, C. Meeldijk (2022b). Assessing the potential damage of a Bruce anchor when pulled against an Offshore windfarm infield electricity cable. Wageningen Marine Research Letter report in prep.	In this study the damage that a standard Bruce anchor could inflict once it was pulled through/collided with an infield electricity cable was investigated. At the maximum force marine conditions can provide only superficial damage of the outer mantle was observed.
Stability of the crab-pot-strings when using dahns and Bruce anchors	Rozemeijer M.J.C, C. Chun, R. Cramer, A. Korving, C. Meeldijk (2021b). Assessing the stability and mobilisation of crab-pot-strings anchored with Bruce anchors under different marine conditions. With information of	In this study, the chance of mobilisation of crab-pot-strings when using dahns and Bruce anchors as part of the risk formula was investigated.

	catchment of brown crab (*Cancer pagurus*), European lobster (*Homarus gammarus*) and other species. Wageningen Marine Research Report Stability of the crab-pot-strings when using dahns and Bruce anchors C107/21	
Defining a haul-out indicator	Rozemeijer M.J.C, Cramer R., Deetman B., Korving A. (2022c). Defining a haul-out indicator for removal of crab-pot-strings in Offshore Windfarms under anticipated adverse weather conditions. WUR Wageningen Marine Research report C052/22. https://doi.org/10.18174/576836	In this study a haul-out indicator was defined based on wind surge, significant wave height and swell. When predicting a defined threshold, the crab-pot-strings should be hauled out

3 Results

The different steps and results are explained in chronological order.

3.1 The disfunction of chains

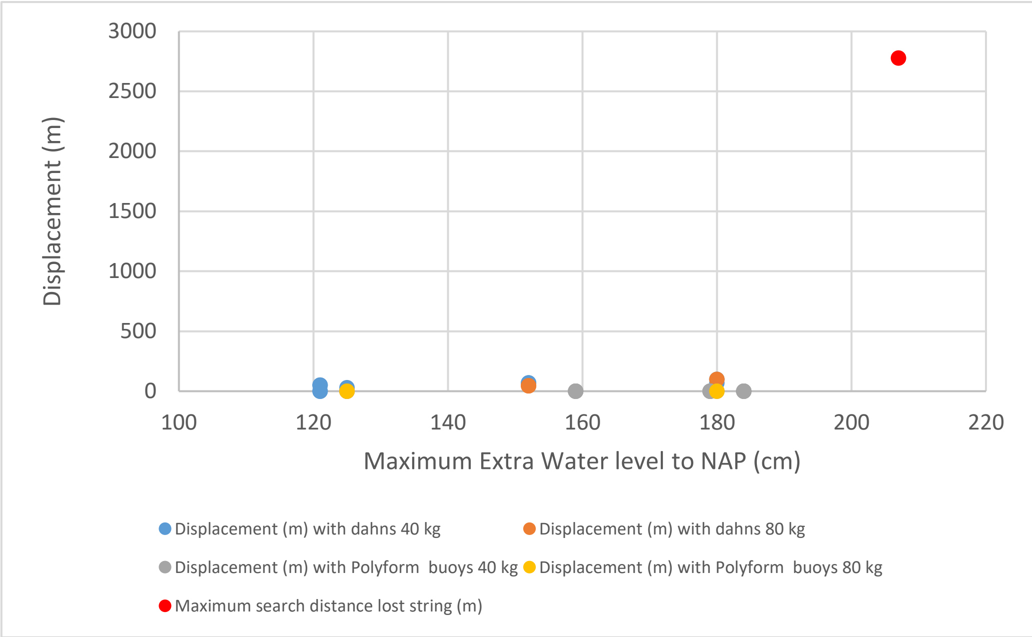
In general, passive pot fisheries on crab and lobster with cages are performed with chains because anchors have a low holding performance in the stony seabed and hard substrates. Materials like chains and dahns are described in Annex 2. Stony and hard substrate are a typical habitat for brown crab and thereby profitable brown crab fisheries. In general, fishermen experienced that dahns destabilise the crab-pot-strings (C. Meeldijk, pers. obs.), usually round Polyform A1 buoys (fenders) are used to mark the positions of the crab-pot-strings. Both because of legal obligations (EU 2005, Article 12: EU 2011, Article 15) and better visibility for Crew Transfer Vessels (CTVs) operating in the OWF (Rozemeijer et al., 2020), dahns are obligatory to mark the crab-pot-strings (also on open sea).

In a first test it appeared that the combination of dahns with chains is an unstable setup. At maximal water level as compared to Normaal Amsterdams Peil (NAP, indicative of wind surge and thereby currents) of 1.21 m and higher, crab-pot-strings with dahns were mobilised (Figure 5A,B). At 2.07 m maximum water level as compared to NAP the tested crab-pot-string disappeared beyond the 2,778m stretching search survey. Half-moon shaped searches were made of maximally 2,778 m extent (1.5 nautical mile) in the direction of the flood current (North East) of the original position but the crab-pot-string was not found (Korving et al., 2021, Rozemeijer et al., 2022a). No difference was found between an anchoring chain bunch of 40 kg or 80 kg. The crab-pot-strings setups with fenders (polyform buoys) were stable with water levels as high as a maximal water level as compared to NAP of 1.80m.

With these results, a risk evaluation session was held with the stakeholders (Eneco, CTV services, representatives of the Government of the Netherlands[2] and team members, 14-01-2021) where the use of fenders instead of dahns was discussed. Eneco accepted the use of fenders in the assurance that positions of the crab-pot-strings would be made known to all CTV captains (WMS, Rozemeijer et al., 2020). In addition, every time upon redeployment, the new, perhaps slightly deviating, positions were to be reported to both Eneco and the Coast Guard. However, the use of fenders is not allowed by EU legislation (EU 2005, Article 12: EU 2011, Article 15) and the dahns with registration numbers of the fishery vessel are obligatory. No exemption on this EU legislations could be made on a national level, since it is a competence on the European level.

[2] Ministry of Agriculture, Nature & Food Quality and Rijkswaterstaat

A



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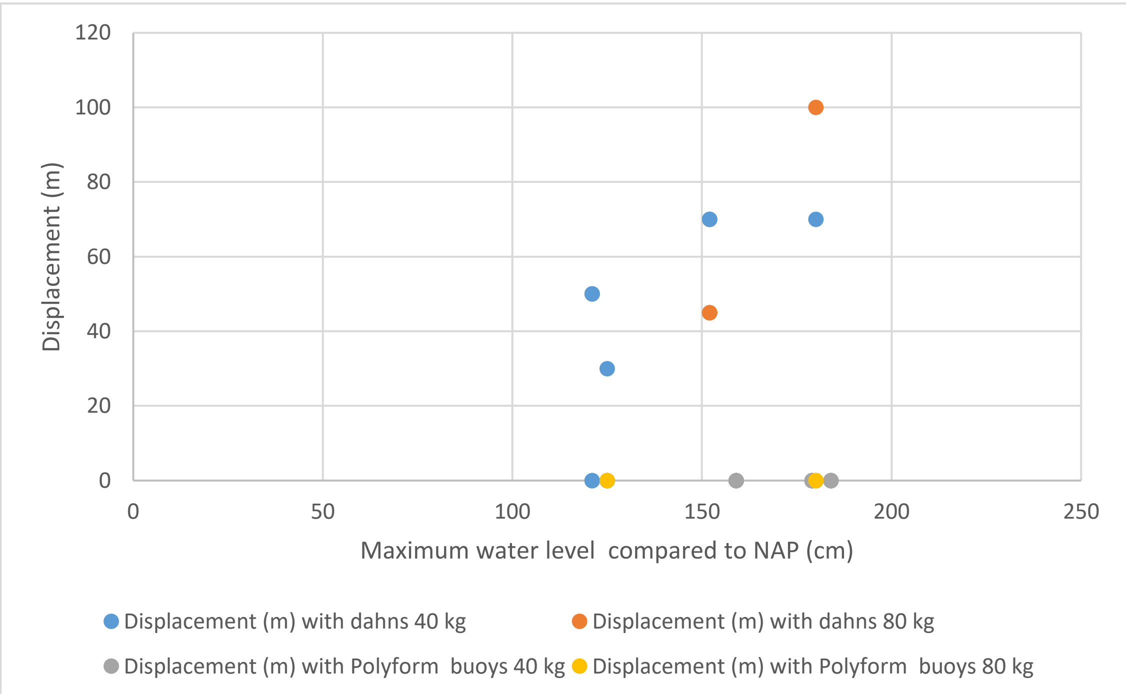


Figure 5 Displacement of the crab-pot-strings with dahns & bundles of chain and crab-pot-strings with polyform buoys & bundles of chain in relation to Maximum water level compared to NAP (cm). The point at 2,778 m in A is the maximum search distance in North Eastern direction of a lost string. The two points of 45 m displacement were averaged over an estimated range of displacement of 40-50 m.

A: with the data point of the lost crab-pot-string.

B: without the data point of the lost crab-pot-string.

Figure 6 The infield electricity cable with a diameter of 146 mm. The cable is made from (outside to center): 1. Raffia cover (very thin); 2. Thin bitumen layer; 3. Galvanized steel wires; 4. Bitumen coating; 5. Three electricity cables with a similar structure.

3.2 Testing modified Bruce anchors

In the risk evaluation session of January 2021, it was decided to study the risk of using modified Bruce anchors with modifications to prevent the hooking into the infield electricity cable. These tests were performed with an obtained infield-electricity cable that was of the same design and construction as the Eneco infield electricity cable (Figure 6) but was slightly thicker (146 mm instead of 113 mm diameter, see also Annex 2 for cable specifications). Altogether two types of default Bruce anchors were tested and five modified variants (Rozemeijer et al., 2021a):

1. The Bruce anchor (or M-anchor, default 1), galvanized 10 kg, as supplied by CIV Den Oever U.A. (Figure 7A), fluke and shaft nearly parallel.
2. A second Bruce anchor (Figure 7B), galvanized 10 kg, with a slightly larger angle between fluke and shank (default 2).
3. Modified Bruce anchor Variant 1: 3 bars, (Figure 7C): from each end point of a fluke, a bar was welded to the stem to prevent the anchor from hooking on the cable.
4. Modified Bruce anchor Variant 2 (Figure 7E): 1 bar, but one bar instead of three.
5. Modified Bruce anchor Variant 3 (Figure 7D): 3 cut-through bars, like variant 1 but with each bar 2 cm was removed from the fluke to possibly improve the burial ability.
6. Modified Bruce anchor Variant 4 (Figure 7F): 3 steel cables, as variant 1 only the bars were replaced by steel cables.
7. Modified Bruce anchor Variant 5 (Figure 7D): 3 ropes, as variant 4 in which the steel cables were replaced by thin rope (size 3 mm).

Figure 7
A: Bruce anchor default 1. B: Bruce anchor default 1 (upper, outer) and 2 (lower, inner, with the red tape) demonstrating the larger angle of Bruce anchor default 2. C: Modified Variant 1 with three bars. D: Modified Variant 5 with three thin ropes (foreground) and Modified Variant 3 with cut through bars (background). E: Modified Variant 2 with one bar. F: Modified Variant 4 with three steel cables. Enlarged pictures can be found in the Annex 2 (Figure 14 to Figure 20).

It was shown that a modified Bruce anchor with three bars from each fluke to the shaft did not hook into the infield-electricity cable, whereas the Bruce anchor default 1 did hook into the infield electricity cable (n = 10 for both, done on the higher beach, dry sands). During the tests it was noticed that the Bruce anchor default 1 dug in well during pulling. The sand came up to the horizontal shaft. Variant 1 (three bars) only partly dug in the dry sand of the high beach. The sand did not reach the top of the vertical shaft.

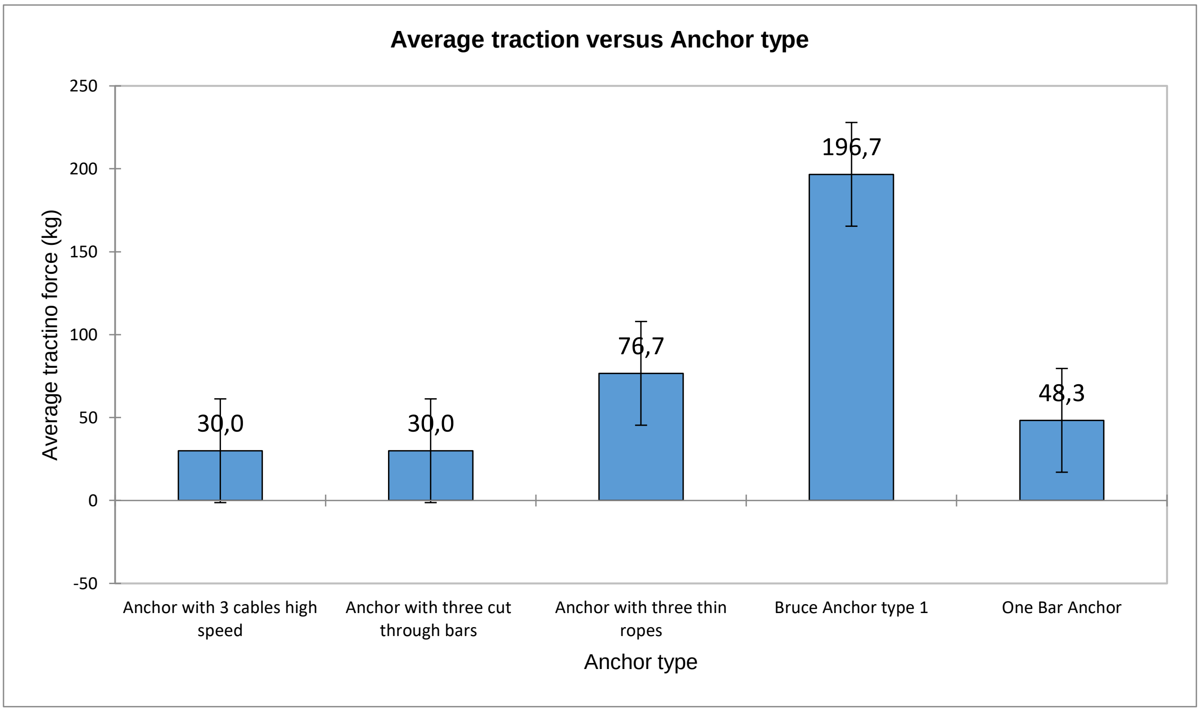


Figure 8 Average traction of the default 1 Bruce anchor compared to four types of modified Bruce anchors to prevent hooking into an infield electricity cable. The Bruce anchor default type 1 has a significantly higher average traction force (p: 0.002, at a pulling speed of 4.5 km/hr, without forerunner chain) indicating a better dig-in ability (from Rozemeijer et al., 2021a). From left to right: Anchor with 3 cables: Modified variant 4; Anchor with three cut through bars: Modified variant 3; Anchor with three thin ropes: Modified Variant 5; Bruce Anchor Type 1: Default type 1. One Bar Anchor: Modified Variant 2.

It was decided to test all Bruce anchors (default and modified) for their burial behaviour. The burial behaviour was approximated by the measured traction that was needed to pull the Bruce Anchor through the water saturated sand in the surf zone of the beach. The less traction force was needed, the less resistance given and thus less dug in (Figure 8). The traction was measured with a 500 kg and 1000 kg loadcell in the pulling rope (with a PAT-KRÜGER TR150 Reader). The water saturated sand in the surf zone of the beach was chosen to approximate the water saturated sea bed. The maximum speed of pulling (by tractor) was 4.5 km/hr representing the maximum velocity of sea currents.

Both Bruce anchor default 1 and 2 were tested with and without an iron chain as forerunner to describe the normal work method. There was a difference between the two anchors. Bruce anchor default 2 had less traction force (was less well dug in) as compared to Bruce anchor default 1, despite the fact that the hook of the shaft with the blade was larger, suggesting a better grip. Bruce anchor default 1 hauled at a lower speed also generated lower traction force (Table 4).

All five modified variants did not dig in well into water saturated sand as compared to the default Bruce anchors (Figure 8). As a result, these modified Bruce anchors are not deemed suitable to securely anchor crab-pot-strings in any location.

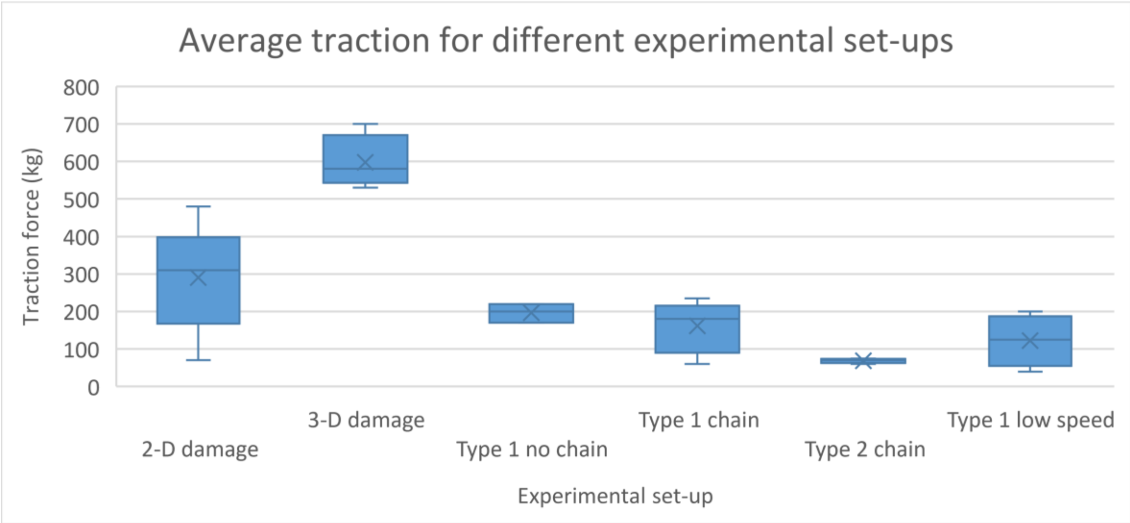


Figure 9 Box-and-Whisker plots of the Average traction of the default Bruce anchor (type 1) causing 2-dimensional damage vs the default Bruce anchor (type 1) causing 3-dimensional damage (significantly different at p= 0.004, dry beach, average speed 2.8 and 3.4 km/hr, respectively) compared to 4 average tractions of tests with the default Bruce anchor (type 1) on the water saturated beach front (Type 1 no chain, 4.5 km/hr, Type 1 chain: also 4.5 km/hr, with a chain as forerunner. Type 2 chain: a slightly different Bruce anchor with a chain as forerunner, 4.5 km/hr and Type 1 low speed, no chain, 1.5 km/hr) (from Rozemeijer et al., 2022b). All other tests were not significantly different from the 2-D damage test (ANOVA). (X in the graph: average; crossbar: median, top limit of the blue bar Standard Deviation (Rozemeijer et al., 2022b).

3.3 Assessing risks of normal Bruce Anchors

In the evaluation of the results of Rozemeijer et al. (2021) (by means of online meetings between WMR and Eneco, WMR and representatives of the Government of the Netherlands[2]), it was discussed to study the risk of using unmodified Bruce anchors resulting in this study on the chance aspect of mobilisation of the crab-pot-strings using Bruce anchors under different weather and hydrodynamic circumstances (c in R=c*D)[3] and the potential damage on an infield cable by a Bruce anchor if the Bruce anchor would get in contact with the infield electricity cable when mobilized.

[3] Equation 1 Risk = chance*damage: R = c*D

Table 2 Comparison of encountered weather and water conditions in 2021 when Bruce anchors were tested with dahns and fenders, and with those conditions in 2019 and 2020 when the dahns and fenders were tested with chains. The maximum and minimum values are given for a period between two haul-outs of the crab-pot-strings (soaking period).The Minimum level at mobilisation gives the minimal value at which strings with dahns and chains were mobilised (Rozemeijer et al., 2021).

	Unit	**Minimum level at mobilisation in 2019 and 2020**	**Maximum level at mobilisation in 2019 and 2020**	**Level at non-mobilisation in 2019 and 2020**	**2021 maximum and still stable**
Maximum wind velocity	m/s	9.4	17.5	11.7	18.0
Maximum 10 min average Wave height	cm	99	337	167	298
Maximum swell	cm	9	90	32	61
Maximum water level compared to NAP	cm	121	207	121	162

3.3.1 Chance of mobilisation

Rozemeijer et al. (2021b) tested the chance of mobilisation of crab-pot-strings using Bruce anchors and dahns during the windy summer of 2021. The maximum and minimum values are given for a period between two haul-outs of the crab-pot-strings (soaking period). The soaking period varied between 1 to 10 days, dictated by weather and water conditions (wind and waves, Figure 10). The crab-pot-strings were firstly deployed on 01-08-21 and definitely hauled out on 18-09-21.

The summer of 2021 had relatively strong winds as compared to other years. During one soaking period maximally 8 Bft occurred for an instant. Three soaking periods occurred with 7 Bft, two periods with 6 Bft, two periods with 5 Bft and one period with 4 Bft (Figure 10, Table 3). The wind periods with 7 and 8 Bft ranged from South-West (222°) to North-North-East (22°).

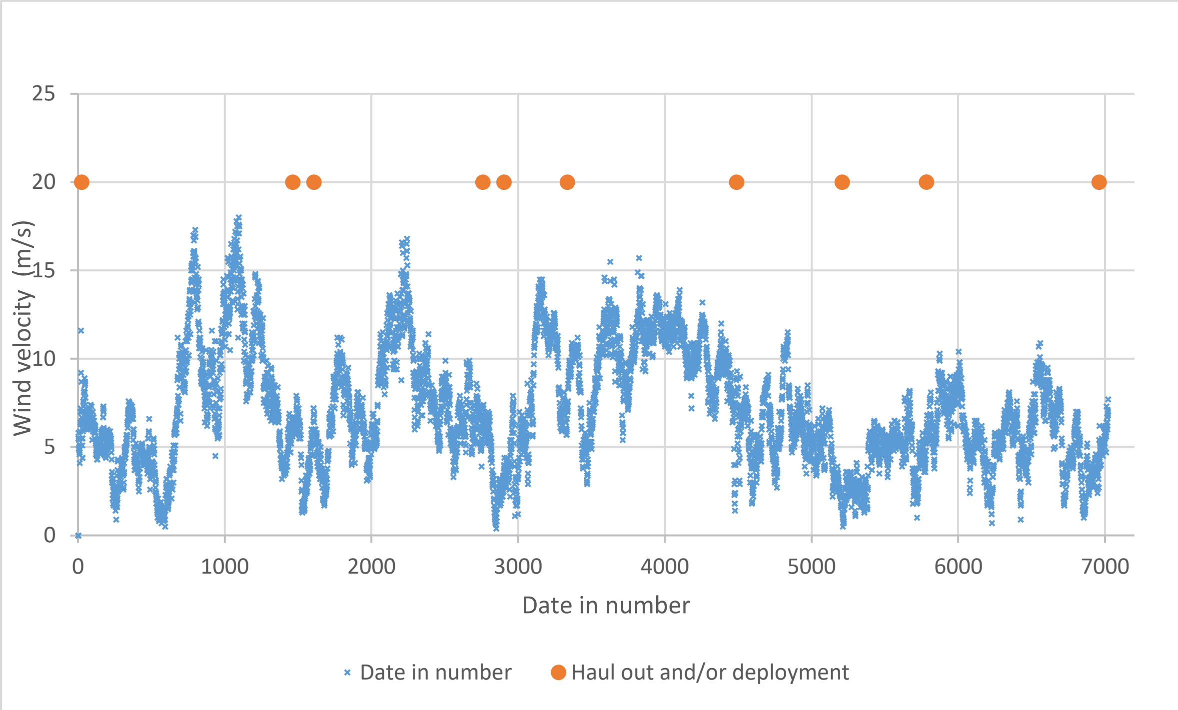


Figure 10 Wind speeds (in m/s) during the experimental period from 1-8-2021 (06:00) till 18-9-2021 (23:50). The orange dots mark the deployment and/or haul-out of the crab-pot-strings. The period between two orange dots is the soaking period. Blue dots are numbered 10 min averaged periods. The wind velocity is converted to Beaufort in Table 3.

Table 3 Scaling the wind velocity in m/s to Beaufort (Bft)

Force (Bft)	**10 min average (m/s)**
0	0-0,2
1	0,3-1,5
2	1,6-3,3
3	3,4-5,4
4	5,5-7,9
5	8,0-10,7
6	10,8-13,8
7	13,9-17,1
8	17,2-20,7
9	20,8-24,4
10	24,5-28,4
11	28,5-32,6
12	>32,6

During the experimental period the average "10 min averaged Significant Wave height" at weather- and water station E13 (in the Eurogeul, Rotterdam, the Netherlands) was 166 cm (with 298 cm as maximum and 57 cm as minimum).

Out of 108 (9 soaking periods*6 strings*2 sides) deployments of anchors, only 1 anchor had moved. It turned out to be tangled in its own rope. That side of the crab-pot-string was moved 40-50m, the other side was not. Table 2 shows that crab-pot-strings with Bruce anchors are not mobilised under circumstances that would have mobilised crab-pot-strings with dahns and chains. The maximum wind velocity was even higher in 2021 as compared to 2019 and 2020.

3.3.2 Potential damage by Bruce anchors

In addition Rozemeijer et al. (2022b) investigated the degree of damage inflicted when Bruce anchors were pulled with force over an infield electricity cable (D in R=c*D)[4]. See Rozemeijer et al. (2022b) for the experimental set-up.

A calibration for comparability is needed due to the difference in set-up as compared to the hook-in tests (dry sand versus water saturated sand). The maximum hydrological speed the North Sea can achieve is 4.5 km/hr. This 4.5 km/hr was taken as checkpoint/benchmark. The water saturated sand set up (Default Bruce anchor type 1, no chain) yielded 196.7 kg traction force at a pulling speed of 4.5 km/hr (Table 4). The damage tests in the dry sands appeared to have higher traction forces: 290 kg (significantly not different from the water saturated traction forces) and 597.5 (significantly different, p: 0.002, Table 4). The traction force is what is causing the damage so results are comparable.

At traction forces comparable to the burial tests with Bruce anchors (slightly higher but not significantly higher, Figure 8, Figure 9, Table 4), the surface of the infield electricity cable looked only superficially touched (Figure 11A). These traction forces are comparable to those maximally experienced when currents mobilize a crab-pot-string and pull it into an infield electricity cable. At most, the raffia layer was a little bit brushed.

[4] Equation 1 Risk = chance*damage: R = c*D

Table 4 Average traction and applied velocity of the default 1 Bruce anchor (type 1) causing superficial (2-dimensional) damage vs the default 1 Bruce anchor (type 1) causing damage deeper into the outer mantle (3-dimensional damage, significantly different at p= 0.004 **, dry beach) compared to 4 average tractions of tests with the default 1 Bruce anchor (type 1) on the water saturated beach front (BA Type 1 no chain, Bruce anchor like the damage test set up; BA Type 1 chain: with a chain as forerunner. Type 2 chain: a slightly different Bruce anchor (default 2) with a chain as forerunner, and BA Type 1 low speed, no chain, 1.5 km/hr) (from Rozemeijer et al., 2022b). All other traction tests were not significantly different from the 2-D damage test (ANOVA). The velocity was statistically not different between 2-D damage and 3-D damage tests (ANOVA).

	Average traction	**St. Dev**	**N**	**Velocity**	**St. Dev**
	Kg		**#**	**Km/hr**	
2-D damage (Default type 1)	290.0	143	6	2.8	0.8
3-D damage (Default type 1)	**597.5	72	4	3.4	0.9
Default Type 1 no chain	196.7	25	3	4.5	
Default Type 1 chain	161.7	65	9	4.5	
Default Type 2 chain	68.8	6	4	4.5	
Default Type 1 low speed no chain	122.5	68	4	1.5	

When higher speeds (3.4 km/hr instead of 2.8 km/hr tractor speed) were applied, significantly higher traction force was observed (p: 0.004, ANOVA) and 3-dimensional damage was observed (Table 4, Figure 11B). It was not possible to establish the volume of the damage. The raffia layer andthe outer bitumen layer were damaged, but the galvanized steel wire protection was not visible in any case (n=4).

Additionally two cases of potential damage on a buried infield electricity cable were studied: buried at 20 cm and 10 cm. The original question was to bury the infield electricity cable in the water saturated sand at the beach front. This was however not possible because the pit filled itself quicker with water and sand than the speed of burying. Legally an export electricity cable is required to have a burial depth of ≥1m. For infield electricity cable there is no legal requirement. However, seabed sediment dynamics will change this burial depth continuously. When buried 20 cm deep the infield electricity cable was not touched by the Bruce anchor (n=3). At 10 cm deep, the surface of the infield electricity cable was touched, and the strings in the raffia layer displaced (Figure 11C, small damage). The bitumen layer was not touched nor damaged. The average surface of the inflicted damage was 5.25 cm^2 (St.Dev 3.39, 4 spots in 3 hauls).

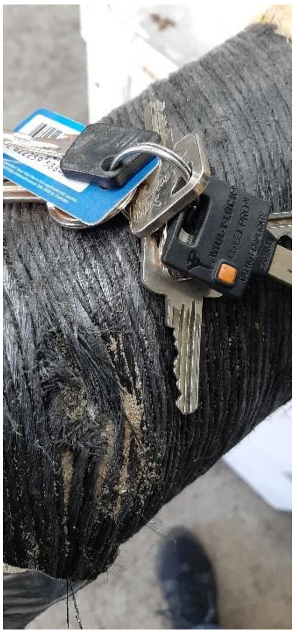
A	B	C
		

Figure 11 The different damages of the infield electricity cable for different treatments:
A: Example of the superficial 2-dimensional damage inflicted while the infield electricity cable was laying on the ground at forces comparable to what the maximal currents of the sea can be (picture taken afterwards in the laboratory).
B: Example of the deeper 3-dimensional damage inflicted while the infield electricity cable was laying on the ground with traction forces >2 times of what the sea can generate. Note that the damage is deeper (3D) but that the galvanised protection wire is still not visible. Picture taken afterwards in the laboratory.
C: Damage when the infield electricity cable was buried 10 cm deep. Note that the raffia threads are displace but no deeper damage was inflicted.

3.3.3 Haul-out Indicator

Crab-pot-strings with dahns have the chance to be mobilised under adverse circumstances whereas crab-pot-strings with polyform buoys have much less chance for mobilisation (Korving et al., 2021, Rozemeijer et al., 2022a). In a mechanistic analysis, explanations are found in differences in three different pulling forces: pulling by currents, pulling by waves and pulling by wind (Rozemeijer et al., 2022c):

1) Dahns have more surface in the water than polyform buoys thereby being more subject to the pulling force of currents (tide and wind surge: Maximum Water Level as compared to NAP).
2) Also the differences in reactions to waves play an important role. The dahns pull in a vertical direction pulsating with a mass of 15 kg to the anchorage instead of the 1 kg of the polyform buoys. Also swell will pull in a similar manner.
3) Of minor importance, the force of the wind on a bladder is also less than the force on the protruding part of a dahn.

Currents and waves should be the main attributes to an indicator for the preventive haul-out of crab-pot-strings in PAWP rather than wind force. Currents are not measured in high resolution. The current is well approximated by Maximum Water Level as compared to NAP. Additionally swell is important in currents and pulling the dahn under water. The wave aspect is well described with the Maximal 10 min. Averaged Wave Height. These three variables are predicted regularly thereby being available for forecasting. The indicator can be defined as:

Equation 2

$Indicator_{Haul\text{-}out}$ = (Maximum Water Level to NAP) + Swell + (Maximal 10 min. Averaged Wave Height)
All in cms (in this case or meters).

In the summer of 2021 no crab-pot-string was mobilized with the $Indicator_{Haul\text{-}out}$ values up to 445 cm. For 2019 and 2020 all the $Indicator_{Haul\text{-}out}$ -out values of >445 cm are either November or March. The highest $Indicator_{Haul\text{-}out}$ value in the summer of 2020 was 440 cm. The strings with polyform buoys and chains were not mobilised by a $Indicator_{Haul\text{-}out}$ of 581 cm. The strings with dahns and chains were already mobilised at a $Indicator_{Haul\text{-}out}$ of 176 cm (Rozemeijer et al., 2022c).

Based on this first limited analysis a calculated threshold value for the $Indicator_{Haul\text{-}out}$ of 445 cm (highest summer value with no mobilisation). Since it is a crucial aspect that has never been tested before in an OWF, this $Indicator_{Haul\text{-}out}$will be used together with an extra safety procedure. In this procedure, fishermen involved in the project will be asked for their opinion on the risk of mobilisation of the crab-pot-strings based on the predictions of the wind and water conditions and their experience. They will evaluate whether there is a risk for crab-pot-string mobilizing circumstances. When they think circumstances will get too adverse, the WMR project leader will contact the Eneco project leader for evaluation (Rozemeijer et al., 2022c).

4 Discussion, conclusions

4.1 Modified Bruce anchors

The modified Bruce anchors did not dig in well. The modifications to prevent the hooking into the infield electricity cable also prevented the digging into the beach sand. It was observed by the authors that the modified anchors "skid" over the sand enabled by the modifications. Modified Bruce anchors are therefore unsuitable to use as anchoring for crab-pot-strings in OWFs or anywhere else. Experts on ship design reflected that modifying anchors is a topic of extensive and costly research (Rozemeijer et al., 2021a). It is therefore not advisable to continue this line of development in the Win-Wind project.

4.2 Risks with anchoring with Bruce anchors

After extensive evaluation it was determined that crab-pot-strings need to be fixated to the seabed with (unmodified) anchors instead of chains. Thereto it was necessary to assess the risk and potential damage of Bruce anchors hooking in infield electricity cables.

4.2.1 Chance of mobilising the strings

The period in which this was tested was the summer of 2021. This summer was particularly windy with several periods with Bft 7 and also maxima to 18 m/s (=8 BFt) as measured at Hoek van Holland. Out of 120 (10*6*2) times, only 1 anchor has moved. It turned out to be tangled in its own rope. That side of the crab-pot-string moved 40-50m, the other side did not move. Concluding: the chance that a crab-pot-string is mobilized at wind speeds up to 18 m/s (8 Bft) is extremely low (independent of the number of anchors per side): Change = 1 (May never occur).

The option of using two anchors at each side of the string was discussed. Given the fact that two anchors on the same side have a higher chance to become entangled makes it a less favourable option. In addition the risk of accidents on board a vessel are higher. The extra wires can easily get entangled with gear or people and pull them overboard. Therefore it is not advisable to work with two anchors at each side of the crab-pot-string (observation A. Korving, captain of the used vessel during anchor stability tests the sea Rozemeijer et al., 2021), although this decision might differ depending on the captain in charge.

4.2.2 Potential damage to the OWF infield electricity cable

With the infield electricity cable uncovered on the sand in the test situation, damage at forces comparable to maximum flow rates encountered during tides and storms was superficial. An infield electricity cable washed open on the seabed is a realistic situation that can occur. The North Sea seabed is very dynamic at the location of PAWP (Smaal et al., 2017).

The outer bitumen sheath was not damaged, the raffia layer at most a little bit brushed at forces comparable to the maximum force the currents can exerts. At forces more than twice as high than can occur under natural circumstances, the outer bitumen sheath of the infield cable on the sand was penetrated. The second layer, however, the galvanised steel mesh, was not damaged. This layer was not even visible because it is so well protected by the outer layers (Figure 11B).

When the infield electricity cable was buried 20 cm in the sand, it was not hit by the anchor. At the infield cable buried 10 cm in the sand, the cable was hit by the Bruce anchor but the outer bitumen sheath was not penetrated. Strings in the raffia layer were displaced but the bitumen below was not visible, let alone the galvanised steel mesh.

In conclusion: The damage from a standard Bruce Anker on an infield electricity cable is superficial in a collision with the maximum force that can be delivered by tidal currents. This applies to an infield electricity cable that is exposed on the seabed and to an infield cable that is buried 10 cm below the surface. The damage = 1 (Negligible: No or insignificant damage to equipment or materials).

4.2.3 Risk evaluation

The normal Bruce anchors pose a very low risk (1) (using Eneco systematics, Annex 1, see e.g. Rozemeijer et al., 2020). In terms of risk categorisation, the chance of a crab-pot-string mobilised is extreme low for wind forces up to 18 m/s (lower 8 Bft at Hoek van Holland): Change = 1 (may never occur). The damage = 1 (Negligible: No or insignificant damage to equipment or materials. The risk is 1 (p*D= 1*1 = 1).

The risks fisheries with crab-pot-strings equipped with dahns and Bruce anchors in OWFs seem acceptable up to 18 m/s wind force (=8 BFt) as measured at weather station Hoek van Holland.

4.3 Haul-out indicator

An $\text{Indicator}_{\text{Haul-out}}$ was defined thereby filling the gap in the WMS for PAWP in which the haul-out indicator was not yet defined. A value was postulated of 445 cm calculated $\text{Indicator}_{\text{Haul-out}}$ (according Equation **2**) for haul-out. The $\text{Indicator}_{\text{Haul-out}}$ was embedded in a procedure with Eneco. In addition extra assurance on the need for haul-out was generated by regularly contacting the fishermen in the consortium and the intended fisherman for the fishing in PAWP for their opinion.

5 Recommendations and suggestions for implementation

5.1 Recommendations for research

5.1.1 Bruce anchor

For the damage part D of the Risk estimation (R= c*D), a practical approach has been used by pulling 10 kg Bruce anchors by tractors through different, rather undefined conditions. In itself these tests could be improved by having more controlled laboratory type approach, yielding more precise results. However the conclusion about damage will not really alter by a more sophisticated approach. In relation to Win-Wind, we therefore advise to stop this part of the research with the 10 kg Bruce anchor, since no improvement in results can be expected.

Bruce anchors are very effective anchors for a sandy seabed like the Dutch coastal zone. In addition they are well affordable for fishermen. Based on present results there is no need to check other anchors for the application with crab-pot-strings.

Other multi-use activities (like e.g. aquaculture or solar installations) which are not easily removed or that remain over winter, will thereby endure much harsher conditions. For that purpose other (modern) anchors like the Rocna anchor or a heavier Bruce anchor could be studied. Here the research should start with the damage aspect. The already extreme low chance of mobilisation further decreases by using heavier Bruce anchors or modern anchors with higher grip.

5.1.2 More extreme circumstances for mobilisation testing

The major gains can be achieved in the mobilisation aspect. Now wind maxima of 18 m/s have been assessed. There was no movement in the strings. More extreme conditions could be assessed as well, e.g. by deploying strings in autumn or spring in order to have higher chances on more extreme conditions. A better and more elaborate description of the chances for mobilisation beyond 18 m/s wind speed can extend the range in which 10 kg Bruce anchors can be applied (beyond 18 m/s).

5.1.3 Haul-out Indicator

The $\text{Indicator}_{\text{Haul-out}}$ needs to be tested further since it is a crucial factor. It is important for the safety within PAWP, it needs to be low enough to assure the preventive functioning. On the other hand, the application of haul-out indicator has large consequences for the profitability of crab-pot-fisheries (Strietman et al., 2022). It has to be high enough to prevent the haul-out where it was not needed. Haul-out requires both costly extra vessel and crew time and reduces the soaking time and thereby catchment opportunities.

A first test period is done during the summer 2022 Borssele II tests in which crab-pot-strings were deployed in the Borssele II OWP. These results still needed to be processed at the time of publishing this report. But in addition, more extreme circumstances might be tested as well since it is such an important factor in need of optimisation. Therefore, it is an option to have strings in the north west corner of the outer safety zone of PAWP during autumn and winter. Then more extreme circumstances can be tested as well. It is advisable not to attach crab-pots to the string in order not to lose valuable material in case the anchor does not hold in these conditions.

5.1.4 Crab-pot-strings perpendicular to the currents

For safety reasons, crab-pot-strings are aligned parallel to the currents (Rozemeijer et al, 2020, 2021b). However Rozemeijer et al. (2021b) suggested that catch efficiencies (catch per unit effort, CPUE) could be less than maximal due to the fact that the bait plume is less well developed reducing the potential income. Since sufficient income for multi-use fisheries on crabs and European lobster in OWF is an issue of concern(Strietman et al., 2022), it is advisable to investigate this option on mobilisation, risk and CPUE.

5.2 Suggestions for implementation

5.2.1 Bruce anchor

Risks are low (1) under the measured conditions of windspeeds of 18.0 m/s (measured at Hoek van Holland). Reducing risks without doing additional research can be found in using heavier Bruce anchors. The chance of mobilising crab-pot-strings will be lower. The intended skipper of the vessel that will be used for the 2023 field study in PAWP has good experiences with 15 kg Bruce anchors.

Depending on the vessel used it might be an option to apply two Bruce anchors on either side. The preference for one anchor on each side was typically for a small ship (in casu < 10m) with limited space with a higher risk for entanglement. Larger vessels will have more space to move and occur outside the high change area for entanglement. It would be wise to consider this option as well.

5.2.2 Buoy line

A potentially effective measure would be elongating the line between dahn and anchor to triple the water depth instead of double the water depth (75 m instead of 50m). That reduces the pulling of waves and currents via the dahns on the anchors (Stefan Tijsen pers. comm.). Thereby it reduces the chance of mobilisation.

5.2.3 Extra survey

An potential additional measure can be an extra survey of the status of burial of the infield electricity cable in the assigned area. Assurance that the infield electricity cables are buried in, reduces the chance aspect.

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7 Quality Assurance

Wageningen Marine Research utilises an ISO 9001:2015 certified quality management system. The organisation has been certified since 27 February 2001. The certification was issued by DNV.

Justification

Report C051/22
Project Number: 4316100277 and 4316100149

The scientific quality of this report has been peer reviewed by a colleague scientist and a member of the Management Team of Wageningen Marine Research

Approved: Linda Tonk
Researcher

Signature: 

Date: 27 December 2022

Approved: dr.ir. TP Bult
Director

Signature: 

Date: 27 December 2022

Annex 1 Eneco Risk assessment methodology

Table 5 Risk matrix (chance * Severity)						
	CHANCE OF OCCURRENCE					
S E V E R I T Y		**A**	**B**	**C**	**D**	**E**
	1	**LOW**	**LOW**	**LOW**	**LOW**	**MED**
	2	**LOW**	**LOW**	**LOW**	**MED**	**HIGH**
	3	**LOW**	**LOW**	**MED**	**HIGH**	**HIGH**
	4	**LOW**	**MED**	**HIGH**	**HIGH**	**HIGH**
	5	**MED**	**HIGH**	**HIGH**	**HIGH**	**HIGH**

Table 6 Description of categories of probability, severity and risk		
PROBABILITY OF OCCURRENCE	**SEVERITY**	**RISK**
A May never occur	**1** Negligible	Low = No immediate action required, proceed with care
B May occur	**2** Moderate	
C Might occur	**3** Serious	Medium = Review & implement preventative measures
D May occur infrequently	**4** Major	
E Will probably occur	**5** Catastrophic	High = Unacceptable. Find alternative method

Table 7 Detailing categories of severity to concrete measurable criteria

SEVERITY	HUMAN	ENVIRONMENT	MATERIALS / EQUIPMENT
NEGLIGIBLE	No or minor injury.	No or insignificant clean up naturally dispersed	No or insignificant damage to equipment or materials
MODERATE	One lost time accident, with no loss of part of the body, or prolonged disability	Clean up requires less than 1day	Damage to equipment or materials with lost time of 1 day production
SERIOUS	Multiple lost time accidents. One injury with loss of part of body, or with permanent disability	Clean up requires approx. 1 week	Significant damage to local area or essential equipment
MAJOR	One fatal injury. Several victims with loss of part of the body, or with permanent disability	Clean up requires approx. 1 month	Significant damage to local area or essential equipment which stops the work until a later date
CATASTROPHIC	Several fatal injuries	Clean up requires more than 1 month	Extensive damage to local area or essential equipment which stops the work totally

Annex 2 Material description

Bunch of chains, dahns and polyform A1 Buoy

Bunch of chains
A length of chain of one meter with shackles of 33cm weighed 40 kg. The two ends were connected together with a rope, and next connected to the eye of the crab-pot-string line. At 80kg it is two lengths of 40kg, where we tied the four ends together at the eye of the crab-pot-string line.

Dahns
The dahn is a floating body whose shape is reminiscent of an enlarged float: a floating body with a bamboo stick of 4.2 m, with a counterweight of 2 kg (Figure 12).

EU (2011) Article 15 Rules for end marker buoys state:

1. End marker buoys shall be deployed so that each end of the gear may be determined at any time.
2. The mast of each end marker buoy shall have a height of at least 1 metre above the sea level measured from the top of the float to the lower edge of the bottom most flag.
3. End marker buoys shall be coloured, but may not be red or green.
4. Each end marker buoy shall include:
    a. one or two rectangular flag(s); where two flags are required on the same buoy, the distance between them shall be at least 20 centimetres flags indicating the extremities of the same gear shall be of the same colour and may not be white and shall be of the same size;
    b. one or two light(s), which shall be yellow and give one flash each 5 seconds (F1 Y 5s), and be visible from a minimum distance of 2 nautical miles.
5. Each end marker buoy may include a top sign on the top of the buoy with one or two striped luminous bands which shall be neither red nor green and shall be at least 6 centimetres broad.

Figure 12 North dahn (one black flag) and the South dahn (two black flags) on a bamboo stick of 4.2 m, with float and counterweight of 2 kg. Danhs are equipped with flashlight and radar reflector.

Polyform A1 buoy
The Polyform A1 buoy is a heavy duty buoy with a ropehold Figure 13. The A-series are made from tough, flexible vinyl materials. The bright orange coloour makes it highly visible. The buoys are resistant to all weather conditions. The A-series buoys are used all over the world for different applications, such as in commercial fishing as net buoys, buoys for long lines, lobster and crab pots, markers and as heavy duty fenders. We have used a buoy with the following specifications: buoyancy 7.8-13 kg, weight: 1.15 kg. Length: 38.0 cm. Diameter 29.5 cm.

Figure 13 Polyform A1 buoy, buoyancy 7.8-13 kg, weight: 1.15 kg. Length: 38.0 cm. Diameter 29.5 cm.

Table 8 Electricity cable specifications

CABLE SPECS	Infield cable	Export cable
Voltage	10/20 kV	170 kV
Diameter	~ 113 mm	~ 196 mm
Approximate burial depth	1000 mm	3000 mm
Weight FXCTV/AXCTV	~ 25/20 kg/m	~ 71.9 kg/m
Tensile strength straight	60/40 kN	100 kN
Tensile strength bend	48/40 kN	60 kN
Armour outer layer 1	Galvanized steel wires	Galvanized steel wires
Armour outer layer 2	Bitumen	Bitumen

Larger pictures of the Bruce anchors (default and modified)

Figure 14 Default 1 and 2 Bruce anchor (with the red tape) demonstrating the larger angle of Bruce anchor default 2.

Figure 15 Bruce anchor default 1 (upper, outer) and default 2 (lower, inner, with the red tape) demonstrating the larger angle of Bruce anchor default 2.

Figure 16 Variant 1 with three bars.

Figure 17 Variant 2 with one bar.

Figure 18 Variant 3 with cut through bars.

Figure 19 Variant 4 with three steel cables.

Figure 20 Variant 5 with three thin ropes cables.

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