Design basis NSF#1

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Contents

1 Version control

Document version nr.	Date	Changes	Remarks	Approval status
0.1	25-11-2022		In work version; all items are preliminary	
0.2	14-12-2022		In work version; first comments incorporate; all items are preliminary	
0.3	15-01-2023		In work version; risk assessment shortened, load cases removed	
1.0	31-01-2023		Included latest concept design. Updated risk assessment. Driving requirements listed.	
1.1	11-05-2023		Recommended design practice, Simply Blue Group, missing parts risk assessment table	Reviewed and signed by NSF 12-05-2023
2.0	16-06-2023		Added comments by DNV Removed pull-out requirement pile anchor	Reviewed and signed by DNV 04-07-2023
2.1	06-07-2023		Design life to 10 year Soil properties beyond 15m depth	

2 Introduction

This document serves as the foundation for designing and engineering the Seaweed Production System within the Borssele wind farm. It outlines the reasoning, criteria, principles, assumptions, and constraints used for detailed engineering and final product design. It also includes key conditions, requirements, project needs, performance criteria, and compliance with legal and code regulations.

2.1 References

Internal documents

[1] 20230330_Recommended_design_practice_v1.0_released, Aqitec, 2023
[2] 20230616_Drawing_NSF1_A0_v2.0, Aqitec, 2023
[3] 20230302_NSF1_structural_v1.1, Aqitec, 2023
[4] 20230302_NSF1_BOM_permit, Aqitec, 2023
[5] 144978-VOOW-TF-ENG-TN-1001 Anchor piles - Soil parameters assessment and geotechnical design recommendations, Van Oord, 2023

External documents

[6] Report - Geological Ground Model, Wind Farm Site III Borssele, Wind Farm Zone Dutch Sector, North Sea, WOZ1500010, Issue 3, Fugro
[7] Metocean study for the Borssele Wind Farm Zone, 1210467-000-HYE-0012, 19 February 2015, final, Deltares
[8] 20150219_SDB_Deltares_Metocean study for the Borssele Wind Farm Zone Site III_Tables_F, Deltares

Codes and standards

[9] NS9415, Floating aquaculture farms Site survey, design, execution and use, 2021
[10] DNV-RP-C205, Environmental conditions and environmental loads, 2010
[11] DNV-OS-E301, Position mooring, 2021
[12] DNV-OS-E303, Offshore fibre ropes, 2018 (amended 2021)
[13] EN1990, Basis of structural design, 2005
[14] EN1993, Design of steel structures, 2005
[15] IALA 1066, The design of floating aid to navigation mooring, 2010
[16] IALA 1099, Hydrostatic design of buoys, 2013
[17] API RP 2A WSD, Recommended practice for planning, designing and constructing fixed offshore platforms – Working Stress Design, 2007
[18] API RP 2GEO, Geotechnical and Foundation Design Considerations, 2011

2.2 Project overview

The consortium of Van Oord Offshore, Simply Blue Group, Algaia and North Sea Farmers will develop the North Sea Farm #1 (NSF#1), with Aqitec providing consultancy on the design. The farm will be integrated into the existing Borssele 3 Blauwwind wind farm, with no pre-determined design criteria or basis available. Safety protocols must be upheld, including maintaining a safe distance from wind turbines, shipping lanes, and infrastructure.

2.3 Mission project

The goal of the NSF#1 project is to support and expedite the growth of a sustainable and eco-friendly seaweed industry, focused on cultivation in the Greater North Sea area. The project prioritizes the following core values:

- Safety and reliability above all else,
- Developing the seaweed sector in an environmentally-conscious and sustainable manner,
- Sharing new insights and knowledge with other stakeholders to further develop the industry, and
- Embracing a pioneering, learn-by-doing approach, while also incorporating best practices from adjacent industries and sectors.

Overall, the NSF#1 project seeks to promote the responsible cultivation of seaweed, with a focus on sustainability and inclusivity. By embodying these values, we hope to create a project that benefits both the environment and the economy.

2.4 Design process

The design process begins by creating multiple design options. These options are then evaluated through calculations and simulations to determine their theoretical feasibility. The design process is flexible, allowing for all aspects to be examined and evaluated. The focus of design optimization can vary, such as minimizing CAPEX or OPEX costs, reducing risk, or reducing environmental impact. During the detailed design phase, the design is thoroughly reviewed, validated, and approved by the lead engineer Van Oord Offshore and external experts.

2.5 Operational considerations

The immediate objective is to establish a feasible practice and, as necessary, use it to continually improve the design principles and requirements outlined in this document. Monitoring the condition of the system, automating troubleshooting, and implementing preventative maintenance are crucial for ensuring a safe, reliable, and well-maintained farm.

Aqitec will conduct internal reviews of the deliverables. External experts will also perform checks and provide approval at all stages of the design process. By maintaining conformity throughout the project, a greater level of autonomy in operating the system 'license to operate' can be achieved. It is recommended that the organization implements a quality management system in line with ISO 9001 standards.

2.6 Project organizational structure

Client	Consortium (North Sea Farmers, Simply Blue Group, Algaia, Van Oord Offshore) delegated to Invest-NL
Project lead	North Sea Farmers
Technical lead	Van Oord Offshore
Consulting Engineer	Aqitec Projects
3rd party validation	Marin
Recommended Design Practice and compliancy design	DNV
Technical advisor (operations)	Simply Blue Group
Technical advisor (installation)	Van Oord Offshore

2.7 Project approval plan

The conceptual design, structural design report and Recommended Design Practice will have to be approved deliverables which are required for the permit application (2022 week 51/52). Due to the short lead-time of these documents, it is not possible to capture all feedback, details and checks before application. Therefore, these documents will be revised in week 15 of 2023. Documents will be shared prior to approval for feedback. Documents in progress do not need to be approved.

The conceptual design, structural design report, and Recommended Design Practice are critical deliverables that are required for the permit application, which is scheduled for week 8 of 2023. Due to the tight deadline for these documents, it may not be possible to incorporate all feedback, details, and checks before submission. Therefore, these documents will be reviewed and revised in week 20 of 2023. They will be shared with relevant parties prior to approval for feedback. In-progress documents do not require formal approval. The table below outlines the necessary approvals and the entities responsible for them.

Table 1: Project Approval Plan

Document	Expected delivery date	Aqitec	North Sea Farmers	Simply Blue Group	Van Oord Offshore	DNV	Marin	Invest-NL
Recommended Design Practice	2022 – Wk 51 2023 – Wk 7	AU	PA		DA	BA		
Calculation method validation	2022 – Wk 47	AU	PA		DA			
Design basis	2023 – Wk 5	AU	PA		DA			
Concept design ‘ready for verification’	2023 – Wk 2	AU	PA		DA			
Structural report	2023 – Wk 7	AU	PA		DA		BA	
Construction and installation plan	2023 – Wk 7	DA	PA		AU			
Production, operation and maintenance plan	2023 – Wk 7	DA	PA	AU	DA			
Structural check Marin	2023 – Wk 12	BA	PA		DA		AU	
Verified design	2023 – Wk 15	AU	PA		DA			

AU – Author. Responsible for the preparation and delivery of the document, including conducting an internal detailed review.
DA – Detailed approval. Responsible for detailed checking of the document. Approval confirms that the document content is checked on correctness.
BA – Basic approval. Responsible for basic checking of the document. Approval confirms awareness of the documents content.
PA – Project approval. Responsible for project control. Approval confirms that the document has been reviewed by the appropriate people, fits its purpose and is ready to be shared (permit requests / certification/ applicable third parties).

3 Concept design

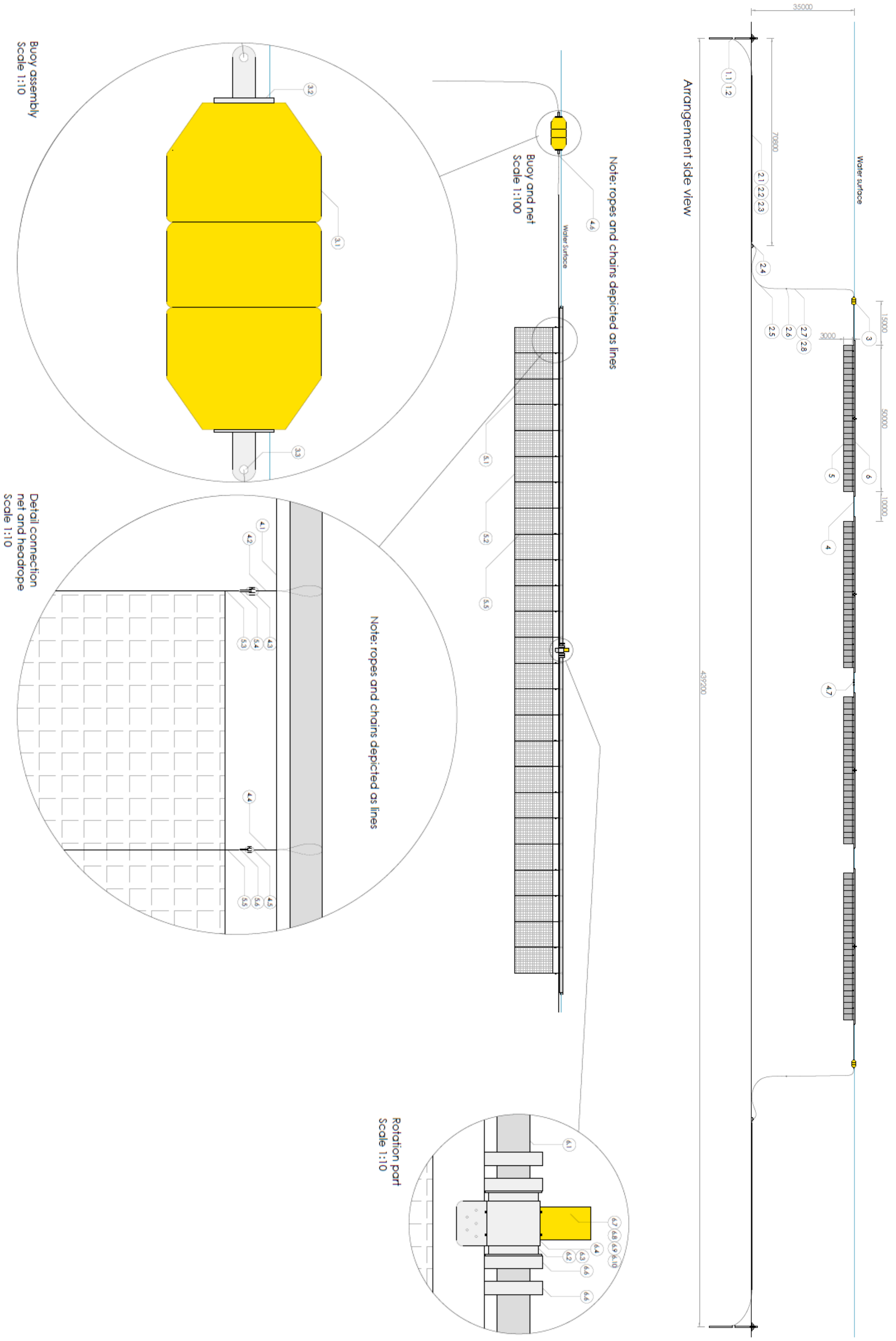


Table 2: Bill of materials

balloon	part number	part name	assys	amount per assy	Purchase Part/ Custom	Material
1	01-001	Pile anchor	2			
1.1	01-001-001	Weldment		1	Custom	Steel S355 or equivalent construction steel
1.2	01-001-002	ECO structure		1	Custom	Steel S355, (pear) wood, shells, degradable rope
2	01-002	Catenary assembly	2			
2.1	01-002-001	LTM anchor shackle (and spacers)		1	PP	R3 or equivalent
2.2	01-002-002	Stud link chain with enlarged end links		1	PP	R3 or equivalent
2.3	01-002-003	LTM Shackle		1	PP	R3 or equivalent
2.4	01-002-004	Concrete block		1	PP	concrete
2.5	01-002-006	Stud link chain with enlarged end links		1	PP	R3 or equivalent
2.6	01-002-007	Swivel shackle - Type A		1	PP	R3 or equivalent
2.7	01-002-008	12 Strand braided rope		1	PP	LANKO®FORCE (Dyneema) or equivalent
2.8	01-002-009	Thimble		2	PP	Galvanized steel
3	01-003	Buoy assembly	2			
3.1	01-003-001	Floaters		1 set	PP	PE / PUR foam or equivalent
3.2	01-003-002	Weldment		1	Custom	Steel S355 or equivalent construction steel
3.3	01-003-003	Pin		2	Custom	Steel StE690 or equivalent
	01-004	Head rope assembly	1			
4.1	01-004-001	8 Strand braided rope		2	PP	TIPTO®EIGHT or equivalent
4.2	01-004-002	Rope loop edge net		8	PP	Nylon or equivalent
4.3	01-004-003	C-link 24mm		8	PP	Stainless steel
4.4	01-004-004	Rope loop net		96	PP	Nylon or equivalent
4.5	01-004-005	C-link 16mm		96	PP	Stainless steel
4.6	01-004-006	Thimble		4	PP	Galvanized steel
4.7	01-004-007	Measurement / load link		1	PP	Steel
5	01-005	Net assembly	4			
5.1	01-005-001	Net		1	PP	PP or equivalent
5.2	01-005-002	Sinker cable		1	PP	Galvanized combination or equivalent
5.3	01-005-003	Vertical rope edge net		2	PP	Nylon or equivalent
5.4	01-005-004	C-link 24mm		2	PP	Stainless steel
5.5	01-005-005	Vertical rope net		24	PP	Nylon or equivalent
5.6	01-005-006	C-link 16mm		24	PP	Stainless steel
6	01-006	Pipe assembly	4			
6.1	01-006-001	Pipe Ø250		1	PP	HDPE 100/ equivalent
6.2	01-006-002	Pipe Ø280		1	PP	HDPE 100/ equivalent
6.3	01-006-003	Wear sleeve		1	Custom	AISI316L or equivalent
6.4	01-006-004	Rotating element		1	Custom	UHMWPE/ thordon/ hakorit/ d-glide or equivalent
6.5	01-006-005	Brackets		2	Custom	AISI316L or equivalent
6.6	01-006-006	Clamping flange pipe		4	PP	HDPE / equivalent
6.7	01-006-007	GNSS unit		1	PP	
6.8	01-006-008	Camera unit		1	PP	
6.9	01-006-009	Radar reflector		1	PP	
6.10	01-006-010	Top light		1	PP	

4 Risk assessment

4.1 Introduction

A risk assessment is conducted for the proposed NSF#1 seaweed farm concept. The purpose of performing a risk assessment at this stage is to identify potential risk factors early in the design process, in order to inform and guide design decisions. The outcome of the risk assessment will impact engineering and design choices. The assessment is conducted on a component level, using a qualitative approach and the expertise of the primary engineering team at Aqitec. The assessment is also informed by the experience and insights of key stakeholders, such as the North Sea Farmers and other industrial partners

4.2 Process

The first step in the process is to present the methodology, with a focus on identifying the types of risks that can be analyzed during the design stage, and the outcomes measures that are relevant for the risk analysis. Next, a system-level and component-level risk identification is carried out, and the risks are classified based on their likelihood and consequences. To present this, the findings are presented in a risk matrix. For risks that are considered unacceptable, risk controls are implemented to mitigate them sufficiently. These risk controls are then described in more detail. The risks that were previously deemed unacceptable are then presented again in their mitigated state using a risk matrix. Finally, the conclusions drawn from the risk assessment are presented.

4.3 Methodology

The risk assessment methodology employed in this study is adapted from the NS9415 standard for fish aquaculture, and is compliant with the general guidelines for risk assessments outlined in ISO 31000 and the assessment techniques specified in ISO 31010. For this study modifications are made to the NS9415 standard, most notably in the outcome measures used. The primary negative impacts include harm to human lives, damage to natural habitats, and loss of property belonging to third parties as a result of equipment failure. This report does not take into account economic risks for the owner/operator.

4.4 Scoring criteria

The outcome measure for severity is associated with the loss of equipment. The risks these objects pose is determined by three factors: The size of the object, whether the object is floating or submerged and whether the object is trackable by a beacon. From this we can draw several conclusions about the potential harms of various objects:

- The potential harms associated with a small to medium floating object that is trackable are small, as the loss of the object can be detected quickly and retrieving the object is feasible.
- Submerged objects that exist just under the waterline pose more potential harm since they cannot be detected visually. Furthermore, it is assumed that the functionality of any beacon is fully obstructed by the water surrounding it. This would substantially increase the chance of sudden unexpected collision should, for instance, the object drift into a busy shipping lane. Furthermore, retrieval of submerged items is deemed very challenging, since they are hard to track, visually or by other means.
- Large floating objects can be equipped with GNSS trackers.

Extreme potential harm is associated with objects that can plough the seabed, causing irreparable harm to infrastructure. A prime example of this would be a large farm unit that is drifting freely after the failure of both anchors. Since the anchoring chain is much longer than the water depth it is dragged across the sea floor once the system becomes disconnected from the anchors. On top of that, because the floating parts provide drag, the system has sufficient force to keep moving despite the drag of the chain.

Some types of failures do not directly result in free-floating objects but need to be included because they significantly increase the probability of occurrence of other risks. An example of this would be the failure of one of the two anchors. Despite the fact that no objects are free-floating, the failure increases the risk of a second anchor failure or equipment collisions, and the associated potential consequences. From this example, it is evident that there is an inherent level of redundancy in the design, and a reduction in this level of redundancy is a negative outcome that needs to be taken into account. By considering this factor, the analysis becomes more detailed and specific.

In conclusion the following factors influence the severity of an event:

- The size of the object that is released
- Whether the object is submerged or floats (visibility)
- If the object is trackable by beacon
- The ability of the object to plough the seabed
- If the event makes other failures more likely

These considerations yield a severity score with which each risk can be classified. See Table 3.

Table 3: Risk severity scores

Severity	**Effect**	
	Loss of redundancy on:	*Release of:*
1	Medium floating object with beacon / Small submerged object	
2	Medium floating object without beacon / Large floating object with beacon	Small floating object
3	Large floating object without beacon Medium submerged object /	Medium floating object with beacon / Small submerged object
4	Large submerged object / object able to plough seabed	Medium floating object without beacon / Large floating object with beacon
5		Large floating object without beacon Medium submerged object /
6		Large submerged object / object able to plough seabed
Small < 50kg and 5 meter length, medium <500kg and 25m length, large >500kg and 25m length		
Consequences of loss-of-equipment are harm to ships (lines in propeller, collision), harm to infrastructure (pipelines, cables) and ecological damage (habitat destruction, entanglement of wildlife, pollution with non-degradable materials).		

Table 4: Risk probability scores

Probability	**Likelihood**
6	Very likely
5	Likely
4	Somewhat likely
3	Unlikely
2	Very unlikely
1	Extremely unlikely

Using these scoring metrics each identified risk can be placed in a risk matrix.

4.5 Risk identification

In order to identify the risks two techniques are used. The first is brainstorming (ISO 31010:2009-B.1.2). This is most important to identify risks coming from outside the system that nevertheless impact the system. The second is Failure Modes And Effects Analysis (FMEA) (ISO31010:2009-B.2.3). The risks associated with each component are recorded in a risk table with the following elements:

- Identifier
- Undesirable event
- Causes
- Underlying causes
- Consequences
- Severity class
- Likelihood class
- Proposed measures

To effectively report identified and analysed risks, we utilize a risk map as per ISO 31010:2009-B.10.3. Two maps are created, one showing risks in their original state without any measures and the other displaying risks after implementing controls. The latter is included in Appendix B. During implementation, it is recommended to conduct further analysis on the most critical risks, such as using a bow-tie analysis per ISO 31010:2009-B.4.2.

4.6 Risk tolerance

It is impossible to eliminate all risks from a project, thus it is crucial to identify and establish an acceptable level of risk.

Table 5: Risk acceptance matrix

Probability Class	Likelihood	Consequence					
		1	2	3	4	5	6
6	Very likely						
5	Likely						
4	Somewhat likely						
3	unlikely						
2	Very unlikely						
1	Extremely unlikely						

Key

- High risk (unacceptable, measures shall be implemented)
- Medium risk (measures shall be considered)
- Low risk (no measures necessary)

4.7 Risk identification and classification

See table Appendix A.

4.8 Risk mitigation

Risk controls can mitigate risks through two approaches: reducing the likelihood of the risk occurring, and decreasing the consequence if the risk does occur.

4.8.1 Component level mitigations

4.8.1.1 Wear reduction

Some components have been identified as having a higher risk of wear.

An effective strategy to minimize wear on the mooring chain is by attaching a weight at the point where the catenary curve is predicted to touch the sea floor. This increases the local friction with the sea floor, which diminishes the movement caused by small forces, while not hindering the chain's ability to withstand high loads. This weight serves as a barrier that isolates the lower part of the anchor chain from the oscillations of the upper part.

Fouling is expected to accumulate on all exposed surfaces of the system. The rough texture of fouling can cause abrasion to nearby components. One way to mitigate this is by ensuring that the system is under sufficient tension to prevent components from rubbing against each other. However, this may not be sufficient, so additional steps such as thorough cleaning of certain surfaces during routine maintenance will be implemented to prevent fouling.

It is suggested to clean the system during the installation of the growing media and at the end of the harvest season. This is not only important for reducing wear-related concerns, but also for maintaining buoyancy and reducing drag.

Connection points are known to be particularly vulnerable to failure caused by wear. To address this, these connections will be made using a tight-fitting thimble and pin design to increase their durability.

4.8.1.2 Wave, current and other environmental load factors

To mitigate risks caused by environmental factors that increase the loads on the system, two controls have been proposed.

The first is to use conservative safety factors on the expected loads and on the required ultimate breaking strength of components, in compliance with the Recommended Design Practice and industry standards.

The second control is to continuously monitor the loads on the system by incorporating a load link into the main structure. This will provide real-time data on the loads the system experiences, which can be used to validate load prediction models and gain a more accurate understanding of factors such as fatigue loading.

4.8.1.3 Corrosion, fatigue, degradation and other material factors

To mitigate the risks associated with factors that affect the materials the system is constructed from, a series of risk controls have been implemented. These controls address all material-related risks and take into account that all these factors may decrease the ultimate breaking strength of the components over time. Therefore, when designing and sizing components, these factors must be considered. As a result of this approach, the following outcomes will be achieved:

- The lifetime of the component is defined.
- An estimation of the total loss of strength over the lifetime of the component is made.
- The component is sized such that the ultimate breaking strength is sufficient at the end of life condition.
- The component is included in the inspection and maintenance program.
- The component is replaced before its service life is exceeded.

Metallic components of the anchoring system that are not electrically isolated are to be made out of materials that are galvanically compatible.

4.8.1.4 Failures stemming from floating debris

Mitigating the risks associated with floating debris is challenging as the amount of debris is beyond the control of design factors. Since the probability of occurrence cannot be reduced, the system must be designed to minimize the impact when a collision does occur. Increasing the strength of each component to reduce the likelihood of failure in the event of a collision would have a negative effect as it would lead to an increase in the size and mass of the components, thereby exacerbating the severity of failure.

The consequence of failures due to bloating debris is minimized using an inherent safety strategy including a cascaded failure approach. An alternative way to look at the floating debris is that the farm actually captures potential harmful free-floating objects and thereby reduces the risk for other infrastructure.

4.8.2 Inherent safety

Due to the large number of risks, simple component level design changes only are unlikely to be an effective manner of mitigating the risks. On system level an inherent safety strategy is proposed. The following principles will be followed:

- Minimize
- Substitute
- Moderate
- Simplify
- Error tolerance
- Limit effect

4.8.2.1 Minimize and substitute

The most severe effects relate to the size of escaping material and the potential ability to plough the seabed. The first of these factors can be mitigated by reducing the size of systems in order to reduce the harm they can cause, should they drift off. This leads to the following design choices:

- The anchoring buoys will not be large and metallic buoys, but instead will be made out of lightweight and unsinkable plastic. This reduces both size and weight, and thereby reduces the harms involved should it break free and collide with other structures.

- The size per unit of pipe and net will be limited to 50m, smaller than the standard 100m sections.

4.8.2.2 Moderate

In some seaweed farm designs the growing substrate has been constrained by the placement of floaters and ballast to stay in a vertical position. In the proposed design the net has the ability to rotate around the headrope. In the case of a collision or high currents this added compliance greatly reduces the load that the growing medium can put on the headrope.

4.8.2.3 Error tolerance: design for failure

The layout of the system resembles a long chain of components. This is true for the system in a functional sense as well.

In the case of overload, such as in the event of a collision with a vessel or large floating debris, the whole chain can be exposed to higher forces than it is designed to endure. The location of failure of a chain with equal strength over its full extend is hard to predict. To mitigate this the design will include a cascaded strength. This means that specific components of the chain have been designed to fail in a specific order, rather than the entire chain being exposed to higher forces than it can withstand. This approach allows for more predictable failure points and will prevent catastrophic failures of the entire system. The main structural components will fail in the following order:

- Net (@ vertical lines)
- Head rope (@ splice)
- Mooring line (@splice)
- Catenary chain
- Bottom chain
- Anchor

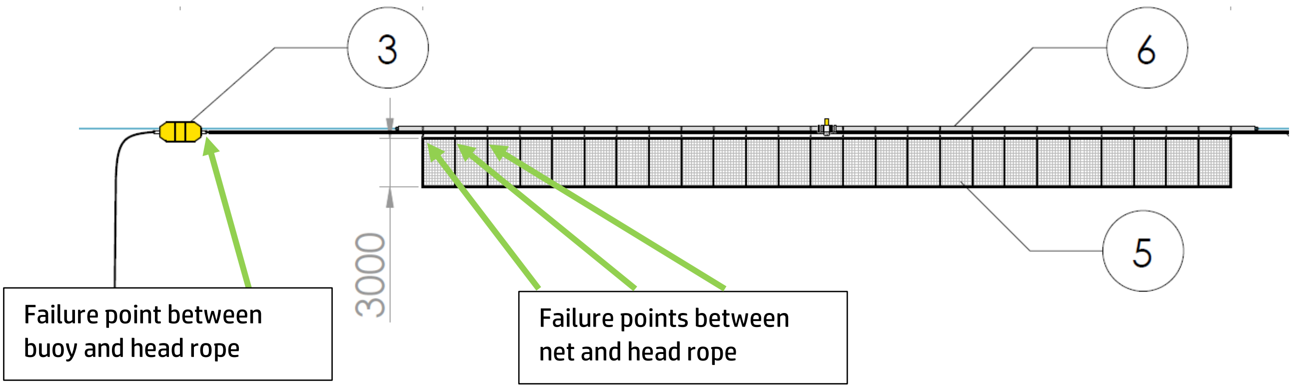
Connecting parts (shackles, pins, thimbles) will have higher strength as compared to the connected parts. A broken part will result in a the Accidental Limit State (ALS) where the system becomes weathervaning (freely rotating) around a single anchor point. Since the system will move in the direction of governing wave or current the forces are reduced.

Failure of two anchor points at the same time is not expected. In case of failure of a single anchor point, the system may collapse and rotate around the other anchor point. A safe distance from other infrastructure must be kept so the moving anchor pile cannot get in contact. Since the mooring chains will act as anchors the movement of the anchor pile is restricted to the surface elements. Proposed safe distance is the length of the surface elements, so length of the head rope + length of the buoys = 265 meter. Risk of a loose anchor pile for other seaweed production systems is limited to damage to the eco-structure. Since the eco-structure is a non-structural part this is allowable.

A weak-link approach is not recommended. This approach would involve inclusion of links that accurately break at a determined load. Thus breaking at an absolute load instead of a load relative to other parts in the system. It is not possible to define an optimal failure load. For some cases the center of the head rope has the highest loads and other cases the terminations have the highest loads. Calculations prove that a weak-link approach will result in unpredictable failure.

Another failure is the severe loss of buoyancy by damage or loss of buoys and pipes. In this case the system will - to some extend - be dragged below the waterline, resulting in reduction of (wave) loads. In case of very severe loss of buoyancy the system will sink to the sea bottom.

In case of capture of a large floating object in the net it is recommended to favor failure of the net before failure of mooring components. A designed failure point is the connecting rope between the headrope and the net. After failure of a single connection point the net can further collapses and other connection points may break. Similar to a zipper, the net will be torn from the head rope. A fully released net will sink to the bottom and will be dragged during maintenance works.



4.8.2.4 Limit effects

If the system loses buoyancy and sinks, it could impact the sea floor near the anchor points. The anchors are to be placed such that in the event of a fully sunk system no part can come into contact with other infrastructure. This can be achieved by defining an exclusion radius around each anchoring pile. For wind farm infrastructure exclusion radii are already defined and will be used in the farm lay-out.

4.8.2.5 Redundancy

A common risk mitigation strategy is to include redundancy in the form of parallel instances of components. For this application, this is not deemed appropriate, as for most of the failure modes this would be equivalent to increasing the strength of the component using a safety factor. Therefore, the primary design safety will be a ´safe life´ design.

4.8.2.6 Beacon

The beacons used to track the system are of importance for tracking and retrieving large floating objects. The beacon systems must remain functional: if the beacon fails a large floating object escalates from severity 4 to severity 5. To ensure the safety and reliability of the system, the following recommendations should be implemented:

1. Install beacons on all large subsystems
2. Ensure that the battery life of the beacons exceeds the service intervals of the subsystems they are attached to.
3. Treat the failure of any beacon as a critical system failure that requires immediate attention and operator intervention.

4.8.3 Operational risk controls
A number of risks can only be controlled using operational measures. These center around monitoring, inspection, maintenance and intervention. Working these out in greater detail is left for the implementation phases. It should include at least the following elements.

4.8.3.1 Preparatory
Prior to first deployment the following controls are to be applied:

- Assembly dry runs
- Contractor instruction and training prior to work at sea to mitigate assembly and installation orders.

4.8.3.2 Remote monitoring
Use of telemetric applications and system monitoring is an effective strategy to control risks.

- Including load links allows the monitoring of the loads in the system. This is used to validate the models used to estimate the loads on the system. Detection of unexpected deviations allows for proactive intervention to prevent system failure.
- Camera monitoring of the system allows for insights not available from other forms of data.
- The monitoring of the positions of the major parts using GNNS systems allows for the rapid detection of change in behavior and aids in the retrieval of any lost equipment. The presence of these beacons is the most effective control to reduce the severity of any incident.

4.8.3.3 On-site inspection and maintenance
The previously described remote monitoring can function to reduce the number of site visits needed, but cannot completely eliminate the need for those. Outside of the visits needed for yearly seeding and harvesting dedicated inspection and maintenance is required. Important elements are:

- Inspection of components including an inspection log. Each component will have a prescribed inspection interval. This enables early detection of faults before failure occurs. Status of each component during each inspection needs to be documented in the projects inspection log.
- Operational checks. Such as on-spot checking assembly work and verifying if installation work is performed to standard.
- Cleaning of fouling. The routine removal of fouling is important for both operational safety and the functioning of the system. Some areas, such as those where increased wear due to fouling may be expected, are to be cleaned thoroughly. Maximum allowed quantities of fouling are to be stated.
- Preventive maintenance program. A preventive maintenance program should be developed to ensure optimal performance and longevity of equipment. The outcome of any inspection should have a predetermined course of action. By incorporating insights from remote monitoring and previous projects into the program, proactive measures can be taken to prevent the need for reactive actions and save time and resources.

4.8.3.4 Intervention
- Rapid response plan. To minimize the potential harm caused by incidents, a rapid response plan should be implemented. This plan should be based on the most likely accident scenarios identified in risk assessments and should include the appointment of individuals responsible for executing the plan. Timely response to incidents is important to prevent accidents.

4.9 Risk map after mitigation
See table Appendix B.

4.10 Conclusions risk assessment
The performed risk analysis has identified a substantial number of risks. The most severe risks factors are:

1. Component failure due to unforeseen environmental, material and design factors

2. Failure of the anchoring system
3. Release of a large and heavy spar buoy. (The pre-risk assessment design included 3100kg steel spar buoys which due to this risk assessment are replaced by a 360kg plastic mooring buoy)
4. The presence of debris

To mitigate these and other risks, controls are to be implemented in the design of the seaweed system. The controls can be divided into the following three groups:

1. **Component level mitigations:** These are interventions on specific (classes) of components such as:
   - The inclusion of safety factors on the strength of components
   - The inclusion of allowances to account for wear, degradation, corrosion, fatigue and fouling.
2. **The adoption of principles of Inherent Safety into the design philosophy:** This has resulted in a broad swath of controls that reduce *severity* of risks where the *likelihood of occurrence* cannot be decreased further.
   - Components of the system have been designed to fail in a specific order, rather than the entire system being exposed to higher forces than it is designed to withstand.
   - This principle allows for predictable failure and will prevent catastrophic failure of the entire system.
   - A minimum radial distance for the anchor points to other infrastructure of 300m is proposed.
   - The pre-risk assessment design included large 3100kg steel spar buoys as catenary buoys. When released (separated from the rest of the system) this type has severity class 4 with beacon, 5 without beacon and when sunk and dragged along the seabed severity class 6. The spar buoys have been replaced by standard 360kg unsinkable plastic mooring buoys. This reduces the severity class to 4 for a buoy without beacon.
3. **Operational risk controls:** These risk controls fall largely outside of the physical design of the system but have important implications for the operational aspects in the implementation stages. These can be divided into the following groups:
   - Preparatory risk controls – changes affecting the operations prior to deployment
   - Operational monitoring – a set of strategies to monitor the system during operation, both on-site and remotely by telemetric technology.
   - Intervention – involves planning of action tying inspection results to maintenance and system failures to interventions.

Note on technical query DNV concerning the concrete block. The design includes a cylindrical 1430kg concrete block at the connection between catenary chain and mooring chain. The block has no structural or mooring function. The function is to limit movement due to wave action and as a result lower the wear of the mooring chain. In heavy sea states the concrete block will move along the seabed and even be lifted upwards. The movement of the concrete block within the 300m radius is considered no risk, even in case of (single) anchor pile failure.

Based on this assessment identified risks can be managed.

5 Requirements and specifications

5.1 Requirement discovery

The requirements for the NSF#1 farm are based on literature study, interviews with consortium and industrial partners, basic engineering information and lessons learned in previous pilot projects.

5.1.1 Literature site conditions Borssele III

[6], [7], [8]

5.1.2 Applicable Codes and Standards

The Recommended Design Practice includes the relevant codes and standards and is the primary basis for the design.

5.1.3 Lessons from industrial partners

Interviews with industrial partners have been done to capture knowledge and experiences. It is recommended to ask industrial partners for sanity checks during further development of the system.

5.2 Site conditions

5.2.1 Seabed / Soil conditions

Bottom topography and bottom type shall be mapped for the entire site, including the extent of the anchoring. The resolution of the bottom mapping shall be at least 10 m × 10 m. Major irregularities, such as large rocks, ridges, fissures or large objects shall be especially noted. (Recommended Design Practice)

Location of the site is indicated in Figure 1 and design values for the soil specifications have evaluated by Van Oord Offshore, additional information on this evaluation and overall site conditions in [5].

Table 6: Design values for soil parameters of the proposed location according [5].

			Submerged soil unit weight	Internal friction angle (low estimate)	Internal friction angle (high estimate)	Skin friction angle (low estimate)	Skin friction angle (high estimate)	Initial modulus of subgrade reaction
Layer	Depth from	Depth to	γ'	LE φ'	HE φ'	LE δ	HE δ	k
[-]	[m]	[m]	[kN/m3]	[°]	[°]	[°]	[°]	[kN/m3]
A	0	0.5	9	30	36	25	31	11.000
B	0.5	3	9	35	41	27	36	22.000
C	3	5	9	29	35	24	30	9.900
D	5	15	10	37	43	30	38	31.000
E	15	18.5	10	35	41	30	36	22.000
F	18.5	25	10	33	39	28	34	16.000

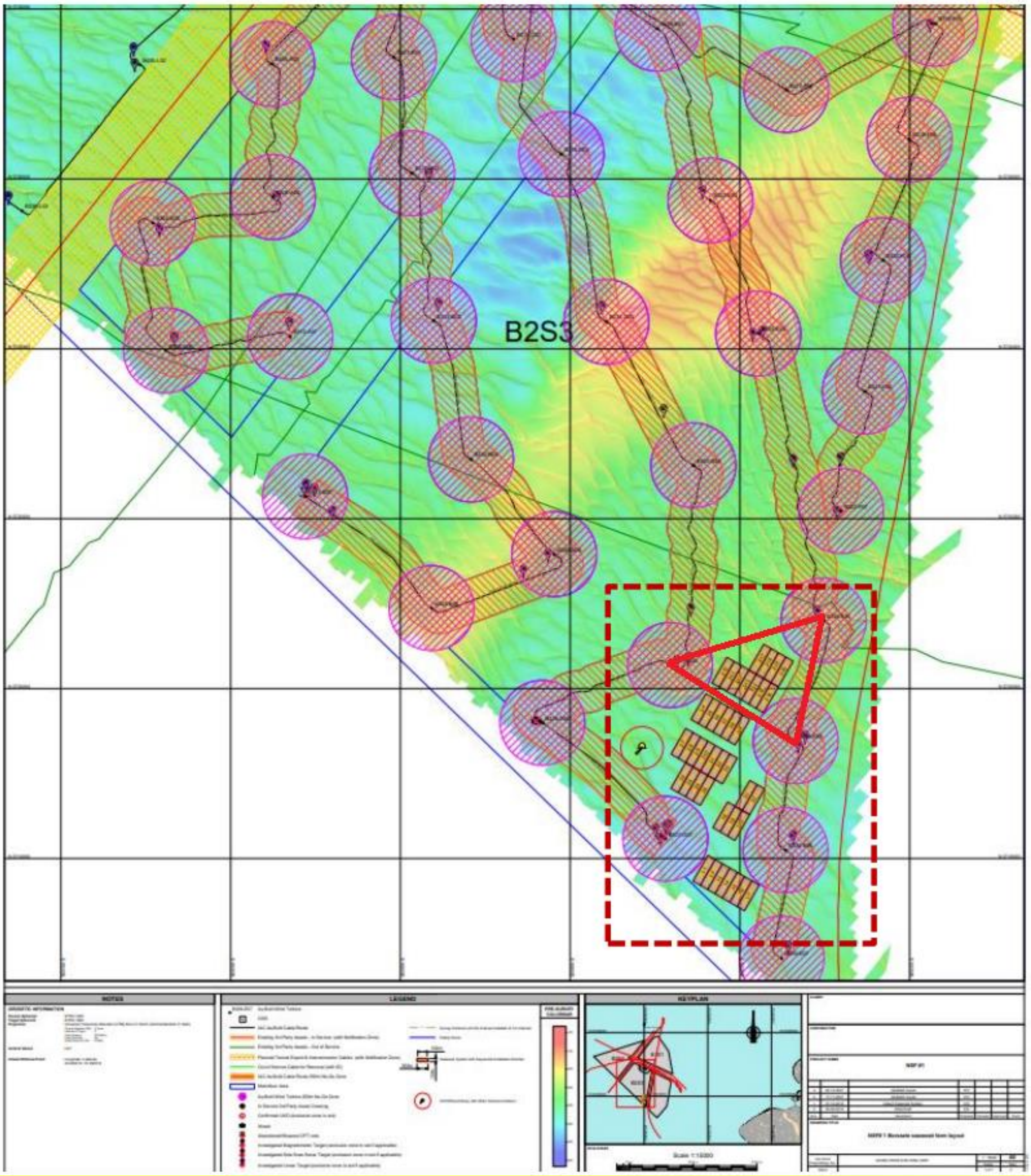


Figure 1: Map of Borselle ||| with proposed location of NSF1 farm in the rectangles within the red triangle bounded by Wind Turbine Generator 323, 324 and 337.

5.2.2 Water level

Table 7: Water level [2]

	Depth [m]	Source
50y extreme maximum	35.0 + 3.1 = 38.1	[2]
Nominal	35.0	Depth at proposed farm location
50y extreme minimum	35.0 – 2.2 = 32.8	[2]

The farm is planned in the southern corner of Borssele plot 3.

5.2.3 Current

Table 8: Currents

Sector	Extreme current at surface Return period = 10y [m/s]	Extreme current at surface Return period = 50y [m/s]
N	1.00	1.04
NNE	1.56	1.66
ENE	1.43	1.54
E	0.86	0.92
ESE	0.64	0.68
SSE	0.67	0.72
S	0.97	1.04
SSW	1.52	1.59
WSW	1.17	1.27
W	0.8	0.86
WNW	0.67	0.73
NNW	0.72	0.78

The extreme current profile is based on depth average current and modelled by the MetOcean report with a power law, with factor α=1/7 according DNV-RP-C205. When using extreme current values further, estimates should be rounded up to 1 digit after the comma. Current directions are given as the going towards direction.

5.2.4 Waves

Table 9: Waves [3]

Values for maximum still water level:				
Sector	**Return period**	**H_s (m) Significant wave height**	**T_p (s) Peak wave period**	**$H_{0.1\%}$ (m) Maximum wave height**
N (345°N: 15°N)	10-yrs	5.83 (5.35 - 6.30)	11.36 (10.79 - 11.70)	10.85 (9.96 - 11.71)
	50-yrs	6.80 (5.94 - 8.01)	12.43 (11.49 - 13.55)	12.66 (11.04 - 14.89)
NE (15°N: 45°N)	10-yrs	4.47 (4.05 - 4.89)	8.70 (8.50 - 9.19)	8.31 (7.54 - 9.09)
	50-yrs	5.36 (4.58 - 6.32)	9.45 (8.88 - 10.05)	9.97 (8.52 - 11.75)
ENE (45°N: 75°N)	10-yrs	3.98 (3.78 - 4.19)	8.37 (8.29 - 8.44)	7.39 (7.02 - 7.79)
	50-yrs	4.73 (4.33 - 5.18)	8.76 (8.69 - 9.12)	8.79 (8.06 - 9.63)
E (75°N: 105°N)	10-yrs	3.28 (3.15 - 3.41)	7.24 (7.20 - 7.23)	6.10 (5.86 - 6.35)
	50-yrs	3.90 (3.62 - 4.23)	7.86 (7.83 - 7.92)	7.26 (6.73 - 7.86)
ESE (105°N: 135°N)	10-yrs	3.01 (2.85 - 3.16)	6.75 (6.68 - 6.90)	5.60 (5.29 - 5.88)
	50-yrs	3.50 (3.24 - 3.87)	7.17 (7.09 - 7.30)	6.51 (6.02 - 7.20)
SE (135°N: 165°N)	10-yrs	3.51 (3.32 - 3.67)	7.13 (7.12 - 7.23)	6.52 (6.18 - 6.83)
	50-yrs	4.19 (3.85 - 4.56)	7.75 (7.67 - 7.92)	7.80 (7.17 - 8.48)
S (165°N: 195°N)	10-yrs	4.62 (4.47 - 4.74)	7.95 (7.90 - 8.00)	8.59 (8.31 - 8.82)
	50-yrs	5.18 (4.89 - 5.57)	8.46 (8.27 - 8.62)	9.63 (9.10 - 10.37)
SSW (195°N: 225°N)	10-yrs	6.10 (5.88 - 6.34)	9.41 (9.34 - 9.46)	11.35 (10.94 - 11.80)
	50-yrs	6.83 (6.44 - 7.37)	9.87 (9.66 - 10.16)	12.70 (11.97 - 13.71)
SW (225°N: 255°N)	10-yrs	6.57 (6.36 - 6.85)	9.71 (9.61 - 9.88)	12.22 (11.83 - 12.74)
	50-yrs	7.50 (7.07 - 8.12)	10.45 (10.29 - 10.77)	13.95 (13.15 - 15.10)
W (255°N: 285°N)	10-yrs	6.55 (6.31 - 6.79)	10.07 (10.07 - 10.15)	12.17 (11.73 - 12.64)
	50-yrs	7.59 (7.16 - 8.10)	10.74 (10.66 - 10.96)	14.12 (13.32 - 15.07)
NNW (285°N: 315°N)	10-yrs	6.03 (5.78 - 6.35)	10.16 (10.05 - 10.20)	11.21 (10.74 - 11.81)
	50-yrs	6.83 (6.23 - 7.63)	10.50 (10.39 - 10.82)	12.70 (11.59 - 14.19)
NW (315°N: 345°N)	10-yrs	6.69 (6.18 - 7.23)	11.51 (11.24 - 11.91)	12.45 (11.50 - 13.45)
	50-yrs	7.90 (6.92 - 9.19)	12.50 (11.77 - 12.89)	14.69 (12.87 - 17.10)

Wave direction are given as the coming from direction.

5.2.5 Wind

Information on local wind conditions can be found in [7] and [8]. However the influence of the wind on the seaweed system is neglected. The model that is used to simulate the ULS, ALS and FLS loads is deliberately prepared not to account for wind, as most of the system is below the water line especially during high sea states.

5.2.6 Ice

Ice is not considered for this location. Both shore-fast and floating ice are outside of the design specifications as confirmed by internal guidelines made by experts at Van Oord Offshore.

Ice accumulation is considered to have very limited effects as the floating pipes in the system are designed to scrape itself clean and the effect of ice accumulation on the buoys is considered neglectable.

5.2.7 Other environmental factors

Effects of earthquakes and tsunamis are not considered as the ‘hazard [of seismicity] is considered to be very low to negligible’ [7].

Extreme water temperature has negligible effects on the material properties and is neglected. (100y return value 21.92 ºC [7]).

Air temperature is not considered to effect the system in a meaningful way as nearly all components are below the water line. For information the extreme 100y minimum and maximum air temperatures are -9.63 ºC and 26.36 ºC respectively.

5.3 Driving requirements

Specifications and requirements are listed below.

Table 10: Driving requirements

Group	#	Specifications and requirements	Origin A) RF, B) Consortium/ Business case C) Industrial partners D) Aqitec/ general
General	1	Applicable recommendations from the Recommended design practice (Regulatory Framework) are to be used in designing of the system	A
	2	Preferably use purchase parts with certification according to the Recommended Design Practice.	A
	3	Murre seeding and harvesting system can be implemented.	A
	4	System is flexible so a future Cultivator system can be implemented.	A
	5	Installation can be done with well available ships; anchor laying vessel, workboat/Multicat, Offshore Support Vessel.	B
	6	Systems are spaced so a large installation vessel (i.e. Offshore Support Vessel and workboat/Multicat) is able to manoeuvre in between.	B
	7	The system should be able to withstand incidental loads from seeding and harvesting vessels.	D
	8	Equipment can be replaced offshore.	B / D
	9	Equipment can handle wear and tear during transport, installation and other operations.	D
	10	Commercial life expectancy of the farm is 10 years.	B
	11	Design life of the farm is 10 years.	B
	12	The mooring system is designed for the commercial life of the farm.	B / D
	13	Unless otherwise specified all components should be designed for a minimum life of 10 years.	A / D
	14	Erosion of the chain and seabed must be kept to a minimum.	D
Arrangem ent	15	One pile anchor at each end of a system.	B
	16	Each system has 200m total net length.	B
	17	Height of the nets is 3m.	B
	18	Two anchor buoys are included for marking and support of the mooring catenary.	C
	19	Arrangement are in line with the governing tidal current; SW to NE / under 45 degrees with meridians.	D
	20	Connections between metal parts prone to 0-load situations will have a narrow fit and prevent jiggling.	D
	21	No use of toxic materials: - No toxic anti fouling coatings or agents. - No use of toxic metals (e.g. lead, copper). - No use of unstable or toxic polymers.	D
	22	Preferred materials are biodegradable and/or recyclable.	D
	23	The arrangement is able to support severe marine growth: - The system has enough floatation to support 20mm thickness of marine growth on parts that are cleaned every year (head rope). Calculate with 1300kg/m3 weight (DNV-OS-E301). - The system has enough floatation to support 150mm thickness of marine growth on parts that are not cleaned every year (anchor line, buoys) up to 7 meter depth. Calculate with 1300kg/m3 weight (DNV-OS-E301). - The system has enough floatation to support 50mm thickness of marine growth on parts that are not cleaned every year (anchor line, catenary chain) deeper than 7 meter. Calculate with 1300kg/m3 weight (DNV-OS-E301). - The HDPE pipe is considered to be self-cleaning. - Seasonal parts (nets, slings) have limited marine growth (other than seaweed).	[1] C C

	24	The system will not entirely sink with loss of one floating element (buoy, pipe).	D
	25	The system is flexible; rigid elements (large buoys, buoys with large water-piercing surface, stiff lines, drag plates, high buoyancy floats) should be avoided.	D
	26	All equipment should be designed to be handled with hoisting equipment.	D
	27	All equipment should be designed to be easily cleaned by a pressure washer.	C / D
	28	All equipment should be designed to be easily inspected.	C / D
	29	Materials should be selected with a minimum degradation due to seawater, UV and dynamic loads.	D
	30	Parts are marked with traceable identifiers.	A / D
	31	Criteria for allowed wear are available.	
Anchor	32	Pile anchors are the preferred anchoring system.	B
	33	Pile will be installed using a vibratory hammer.	B
	34	An anchor shackle will be used as connection between anchor pile and chain.	B
	35	The load capacity is modelled using soil resistance-deflection (p-y) curves method described in API RP 2A.	A / D
	36	The design allows for local scouring of 1,5xD and global scouring of 1,7m	D
	37	The pile and connecting chain are to be designed for a lifetime of 10 years.	A
	38	The pile is connecting to a chain.	A
	39	A minimum distance for the anchor points to other infrastructure of 300m is proposed.	Risk assessment
	40	At end-of-life the pile is retrieved by attachment of a vibratory hammer	B
Chain	41	Product information from supplier Sotra is used.	D
	42	Chain has sufficient length above the waterline (i.e. 10 meter or more) to be pulled on deck while being connected to the pile.	B
	43	Anchor chain segment with highest wear (expected between catenary and seabed) can be hoisted above the water line.	D
	44	Chain is dimensioned so to have sufficient strength remaining at end-of life	B
	45	Twist of chain links should be avoided. Stud link chain is preferred.	D
	46	Must include a swivel to prevent twist in the chain.	D
	47	Use of Kenter and pear shackles and quick release links is not preferred (NS9415 & DNV-OS-E301 8.1.4).	A
	48	If chains are used in or above the splash zone an adequate allowance on diameter should be selected. Use DNV-OS-E301 for corrosion allowances.	A
	49	An adequate corrosion allowance on diameter of the bottom chain should be taken into account. Use DNV-OS-E301 for corrosion allowances.	A
	50	Chain is offshore mooring grade R3.	A
	51	Design life of the catenary chain and transition between seabed and catenary is 5 years.	D
Mooring and head opes	52	Product information from supplier Lankhorst is used.	D
	53	Design life of ropes is 10 years at minimum.	A
	54	Plaited or braided rope constructions are preferred in favour of 3-strand and twisted constructions.	C / D
	55	UV resistance should be considered. Ropes can be stored without cover on land only for short periods.	C / D
	56	Abrasion resistance should be considered.	D
	57	When used in top of water column the rope preferably has a specific gravity lower than water (floating).	D
	58	When used lower in water column the rope preferably has a specific gravity higher than water (sinking).	D
	59	Ropes should be resistant to shocks.	D
	60	Use thimbles with a bending radius to prevent stress concentrations.	D
	61	Preferably include additional provision around thimbles to prevent chafing.	D

	62	Ropes that are expected to rub during handling must (locally) have a provision to prevent chafing.	D
	63	Rated load of terminations that make use of splices should be calculated with 10% reduction in capacity. (NS9415 – Table 11 “The material factor for ropes includes a deterioration of up to 10 % due to splices”.)	A
	64	The fibre rope shall not be in contact with the sea bed during service (DNV-OS-E303).	A
	65	The entire length of fibre rope mooring line shall be submerged at all times during service (DNV-OS-E303).	A
	66	The load-bearing parts of the line shall be adequately protected from marine growth.	D
	67	Hard marine growth shall not be in contact with load-bearing fibres (DNV-OS-E303).	A
Pipes	68	Design information from supplier Pipelife is used.	C
	69	Design life of pipes is 10 years minimal.	D
	70	Main floater is HDPE pipe; PE 100 resin.	C
	71	Minimal pipe diameter for seeding and harvesting machine is Ø180mm.	C
	72	Main pipe has 50 meter segments connecting to the head rope.	C / D
	73	Each pipe segment has a rotation part.	C / D
	74	Pipe has high impact resistance.	D
	75	Rotation parts are designed for minimize wear in nominal operation.	D
	76	Rotation part is able to transfer axial loads from pipe and net to the head rope.	D
	77	HDPE pipe is relatively load free.	C / D
	78	Stress concentrations are prevented.	D
	79	Pipe-net structure can be tugged.	D
	80	All floats are marked with an identification plate with information: ID no, reference to NS9415:2021, type designation (dimensions, weight), production date (mm/yyyy), design work life, maximum allowed load with reference to certificate with ID no, manufacturer. (NS9415:2021)	A
	81	Coefficients of thermal expansion of attached flanges, sleeves and other clamping appendages should be evaluated. No plastic deformation (creep) of the pipe is allowed for air temperature between -20 and 35 deg C.	D
	82	Coefficients of thermal expansion of attached flanges, sleeves and other clamping appendages should be evaluated. No failure of the pipe is allowed when stored in direct sunlight (surface temperature up to 80 degrees).	D
	83	Maximum scratch depth is 10% of pipe wall thickness.	Supplier
	84	Minimum bending radius for SDR21 class pipe is bending radius/OD is 25. This is equivalent to 2.9% strain for a Ø 250x11.9 pipe.	Supplier
	85	Design takes into account the viscoelastic properties and change in E-modulus for range of temperatures.	D
Net	86	Product information from supplier Nettenfabriek or CIV Den Oever is used.	A
	87	Net total length is 200 meter divided in segments of maximal 50 meter.	A
	88	Net material should be soft for attachment of seedlings.	C
	89	Net material can elongate while maintaining planar shape.	C
	90	Net material should preferably be white.	C
	91	Net material should preferably have an open structure.	D
	92	Net material should not shorten (contract) due to absorption of dirt and cycle of wetting/drying.	D
	93	Proposed net construction has maximum mesh size of 200mmx200mm to prevent capture of fauna. System is able to include different mesh sizes.	C / D
	94	Meshes are perpendicular to the pipe (recommended for automatic cleaning, harvesting, seeding).	C
	95	Net is connecting to the head rope and sinker rope with additional length; for each meter of head rope and sinker rope a 1,1 m length of net is used.	C
	96	Recommended net material is thermoplastic polyolefin material (i.e. polypropylene).	C

	97	Net includes a sinker rope in the bottom end to reduce motions of the bottom chain.	C
	98	Sinker rope is made of Hercules rope or other sea water resistant metallic material.	C
	99	Net is attached to slings.	C
	100	Slings are made of wear resistant material (i.e. PA, nylon, mix).	C
	101	Slings have clearance around HDPE pipe.	C
	102	Net is positioned 0,5m under water line.	C
	103	Slings may contain (soft) shackles between head rope and net.	D
	104	Nets can be detached from the pipe and head rope.	D
	105	Slings are connected to the sinker rope.	D
	106	Slings have a lower strength compared to the head rope.	D
Shackles	107	Preferably use minimum amount of shackles	D
	108	Shackles must always be tensioned; either pre-tension or pulled down in catenary.	D
	109	Bolt shackles, screw pin shackles and aquaculture shackles are not recommended.	D
	110	Shackles are preferably not used in or above the splash zone.	D
	111	Shackles should not have protruding or abrasive elements when in proximity of soft materials (e.g. rope, plastic buoys, …). Examples are sharp threads, cotter pins and release pins.	D
	112	Shackles (D or H) used in permanent mooring lines should be LTM type.	D
	113	Shackles connecting the anchor should be according to DNV-OS-E301 and DNV-OS-E302 .	A
	114	Shackles connecting the anchor should have grade R3 or higher.	A
Aton and monitorin g	115	AIS may be included on pipe swivel points.	D
	116	Top light may be included on pipe swivel points.	D
	117	Radar reflector may be included on pipe swivel points.	D
	118	GNSS beacon is included on floating objects with 500kg or more displacement.	D
Catenary buoy	119	Design according to Eurocode EN1990 and EN1993, NS9415, IALA 1066, IALA 1099 and DNV-OS-E301Ch2Sec4.	A
	120	Buoys and floaters are preferably unsinkable; core material (e.g. closed cell foam; PU foam, PIR, EPS, EVA or PVC foam) with sufficient buoyancy to prevent sinking after damage of outside material.	D
	121	Water cannot come in contact with foam core material.	D
	122	Buoys preferably have a connection that facilitates pivoting/swivelling.	D
	123	Floaters shall be supplied with an identification plate located in a clearly visible and easily accessible place. (NS9415:2021)	A
	124	All floats are marked with an identification plate with information: ID no, reference to NS9415:2021, type designation (dimensions, weight), production date (mm/yyyy), design work life, maximum allowed load with reference to certificate with ID no, manufacturer. (NS9415:2021)	A
	125	Buoys are equipped with a lifting eye above the waterline with an opening of at least 140mm in diameter.	C / D
	126	Load capacity of the lifting eye is equal to the capacity of the anchor connection.	A / D
	127	Load capacity of the lifting eye and anchor connection have a failure load of at least 10 times the buoyancy. (NS9415:2021 Annex D)	A
	128	Buoys and floaters can be fully submerged and are resistant to 0,5 bar pressure.	D
	129	Buoys and floats should preferably have a round, spherical or conical shape to prevent slamming and induce a soft water piercing behaviour.	D
	129	Air-filled buoys shall only be used where the buoy is not an essential part of the function of the anchoring.	D
		Buoy has a yellow colour according to colour scheme of IALA.	D

Appendix A: Risk classification table

Scope

To constrain the analysis the number of components that are analyzed is limited. The following constraints are used:

- The analysis looks at two types of components:
    - (Sub-)assemblies of meaningful size
    - The interconnections between (sub-)assemblies
- Only a small number of types of connections are used in the design
- Risks that apply to all components are grouped into a system-level risk rather than split into multiple risks with bespoke mitigating strategies

Risk classification table

ID	Undesirable event	Causes	Underlying Causes	Consequences	Mitigation Needed	Approved Measures	Probability S Class (1-6)	Consequence K Class (1-6)
1	Collision	Run over by vessel	Poor or failing marking of aquaculture farm	Substantial damage to both vessel and headrope; Release of growing media	TRUE	Mark the site using cardinal buoys; outfit large components with beacon; limit size of parts to fit within 'medium' category.	2	3
		Ice	Very cold winter	Damage to buoys and headrope; Release of growing media	TRUE	Beacons on large components	1	4
		Flotsam	Floating debris; containers, pallets, buoys, etc.	Substantial damage to headrope	TRUE	Condition monitoring	4	2
		Placement of aquaculture farm	Lack of care in site selection	Substantial damage to headrope; Release of growing media	TRUE	Exclusion radius around anchors	1	3
	General component failure	Erroneous environmental data	Erroneous wave data	Entire farm breaks free	TRUE	Conservative safety factors	1	4
			Erroneous current data	Release of seaweed or growing media		Conservative safety factors	1	4
			Erroneous direction data	Release of seaweed or growing media		Conservative safety factors	1	4
		Erroneous strength design	Erroneous material parameters	Entire farm breaks free	TRUE	Conservative safety factors	1	4
			Erroneous methodology for calculation of loads	Entire farm breaks free	TRUE	Condition monitoring	2	4
			Erroneous methodology for calculation of strength	Entire farm breaks free	TRUE	Third party review, condition monitoring	2	4
		Erroneous safety factors	Erroneous industry data	Entire farm breaks free	TRUE	Third party review, condition monitoring	2	4
		Increased loads	Heavy fouling	Entire farm breaks free	TRUE	Cleaning interval	2	4
			Unexpectedly high seaweed yield	Entire farm breaks free	TRUE	Load monitoring	2	4
		Erroneous design basis	Erroneous codes and standards, miscommunication, misinterpretation of previous results, unexpected fault inherent to project objective	Entire farm breaks free	TRUE	Third party review, condition monitoring	2	4
		Assembly errors	Operator error	Entire farm breaks free	TRUE	Hire contractors with domain expertise	2	4
			Faulty instructions	Entire farm breaks free	TRUE	Hire contractors with domain expertise	2	4
		Installation errors	Operator error	Entire farm breaks free	TRUE	Hire contractors with domain expertise	2	4
			Faulty instructions	Entire farm breaks free	TRUE	Hire contractors with domain expertise	2	4
	Contact of boat with anchoring system	Incorrect boat handling	Unexperienced contractors	Failure of single anchoring system; danger to personnel	TRUE	Hire contractors with domain expertise	1	4
		Unfavourable configuration / design of boat				Hire contractors with domain expertise	2	4
		Low visibility or bad marking of anchor line			TRUE	Demarcating the aquaculture farm using cardinal buoys; outfit large components with beacon	2	4
		Unfavourable placement of anchor line				Hire contractors with domain expertise	1	4

2	Mini pile failure	Pile pulled out of seabed	Loaded in wrong direction	Loss of both piles	TRUE	Third party review	1	6
			Not installed under the correct orientation	Loss of redundancy for whole farm	TRUE	Anchor capacity testing	1	4
			Ocean floor locally weaker than expected	Likely loss of both piles	TRUE	Site survey. Anchor capacity testing.	2	4
			Sand transport	Likely loss of both piles	TRUE	Regular inspections Include factor for scouring	2	4
		Wear	Scouring	Loss of redundancy for whole farm	TRUE	Regular inspections Include factor for scouring	2	4
		Overload	Erroneous load estimation	Likely loss of both piles	TRUE	Cascaded failure approach	2	4
		Fatigue	Decreased strength caused by cyclic loading	Likely loss of both piles	TRUE	Condition monitoring	1	4
			Unexpected dynamic behaviour of anchoring chains	Likely loss of both piles	TRUE	Condition monitoring	1	5
		Corrosion	Catalytic coupling with more noble metal	Likely loss of both piles			1	3
			Coating failure due to abrasion	Likely loss of both piles			1	3
		Scouring	Scouring higher than expected due to local soil consistency	Lower load capacity pile	TRUE	Regular inspections Include factor for scouring	1	5
3	Anchoring chain failure	Overload	Erroneous load estimation	Entire farm breaks free; remainder of anchor chain drags across bottom but cannot plough			1	4
		Fatigue	Decreased strength caused by cyclic loading	Loss of redundancy for whole farm		Condition monitoring	2	3
			Unexpected dynamic behaviour of anchoring chains	Unexpected cyclic load on pile that slowly works it out		Condition monitoring	1	6
		Corrosion	Corrosive environment	Entire farm breaks free; remainder of anchor chain drags across bottom but cannot plough		Condition monitoring	2	4
		Wear	Higher than expected abrasion due to motion on the ocean floor	Loss of redundancy for whole farm		Regular inspections	2	3
			Unexpected object on ocean floor	Loss of redundancy for whole farm	TRUE	Conservative safety factors	1	5
		Installation errors	Damage to link during deck handling/ installation	Loss of redundancy for whole farm		Hire contractors with domain expertise	3	3
4	Mooring chain failure	Overload	Erroneous load estimation	Entire farm breaks free	TRUE	Conservative safety factors	2	4
		Fatigue	Decreased strength caused by cyclic loading	Loss of redundancy for whole farm	TRUE	Regular inspections	3	3
			Unexpected dynamic behaviour of anchoring chains	Loss of redundancy for whole farm		Regular inspections	1	3
		Corrosion	Corrosive environment	Entire farm breaks free	TRUE	Conservative safety factors	2	4
		Installation errors	Damage to link during deck handling/ installation	Loss of redundancy for whole farm			3	3
5	Mooring line failure	Overload	Erroneous load estimation	Entire farm breaks free	TRUE	Conservative safety factors	1	4
		Fatigue	Decreased strength caused by cyclic loading	Loss of redundancy for whole farm	TRUE	Conservative safety factors	3	3
			Unexpected dynamic behaviour of anchoring system	Loss of redundancy for whole farm		Conservative safety factors	2	3
		Degradation	Inherent degradation	Entire farm breaks free;	TRUE	Conservative safety factors	2	4
			UV exposure	Entire farm breaks free;	TRUE	Conservative safety factors	2	4
			Fouling	Loss of redundancy for whole farm	TRUE	Conservative safety factors	2	4
		Wear	Abrasion (internal collision)	Loss of redundancy for whole farm		Conservative safety factors	2	4
6	Shackle failure	Overload	Erroneous load estimation	Headrope failure	TRUE	Conservative safety factors	2	4
		Fatigue	Decreased strength caused by cyclic loading	Headrope failure		Conservative safety factors	3	3
		Wear	Friction with connected components due to play in system	Loss of redundancy for whole farm	TRUE	Assure each shackle is pre-loaded continuously	2	3
		Corrosion	Corrosive environment	Entire farm breaks free	TRUE	Conservative safety factors	2	4
		Installation errors	Improper fastening	Loss of redundancy for whole farm		Hire contractors with domain expertise	3	3
7		Overload	Erroneous load estimation	Entire farm breaks free	TRUE	Conservative safety factors, condition monitoring	2	4

	Thimble connection failure	Fatigue	Decreased strength caused by cyclic loading	Loss of redundancy for whole farm	TRUE	Conservative safety factors	2	3
		Wear	Friction with connected components due to play in system	Loss of redundancy for whole farm		Conservative safety factors	2	3
		Degradation	Inherent degradation	Entire farm breaks free;	TRUE	Conservative safety factors	2	4
			UV exposure	Entire farm breaks free;	TRUE	Conservative safety factors	1	4
		Installation errors	Improper fastening	Loss of redundancy for whole farm	TRUE	Hire contractors with domain expertise	2	3
8	Catenary buoy failure	Pressure overload (collapse)	Erroneous load estimation	If outside growing season, will sink to ocean floor and plough	TRUE	Conservative safety factors	1	5
			Insufficient buoyancy	If outside growing season, will sink to ocean floor and plough	TRUE	Conservative safety factors	1	4
		Overload at attachment point	Erroneous load estimation	Catenary buoy escapes and starts floating around	TRUE	Conservative safety factors	2	4
			Too much buoyancy	Catenary buoy escapes and starts floating around			2	4
		Sinking	Leak	If outside growing season, will sink to ocean floor and plough	TRUE	Include redundant buoyancy parts	2	4
			Fouling	Will be under water surface and pull other parts of system under water as well		Conservative safety factors	1	5
		Fatigue	Decreased strength caused by cyclic loading	Loss of redundancy for whole farm	TRUE	Conservative safety factors	2	4
		Wear	Friction with connected components due to play in system	Loss of redundancy for whole farm	TRUE	Use small clearances in connections	2	4
			Abrasion due to internal collision	Loss of redundancy for whole farm	TRUE	Conservative safety factors	1	4
			Abrasion caused by fouling	Loss of redundancy for whole farm	TRUE	Regular inspections	2	4
		Corrosion	Corrosive environment	Loss of redundancy for whole farm	TRUE	Conservative safety factors	2	4
		Installation errors	Damage to buoy during installation	Loss of redundancy for whole farm	TRUE	Hire contractors with domain expertise	2	4
9	Headrope failure	Overload	Erroneous load estimation	Loss of redundancy for whole farm	TRUE	Conservative safety factors	2	4
		Fatigue	Decreased strength caused by cyclic loading	Loss of redundancy for whole farm	TRUE	Conservative safety factors	2	4
		Wear	Friction with connected components due to slack in system	Loss of redundancy for whole farm	TRUE	Conservative safety factors	2	4
		Degradation	Inherent degradation	Loss of redundancy for whole farm	TRUE	Conservative safety factors	2	4
			UV exposure	Loss of redundancy for whole farm	TRUE	Conservative safety factors	2	4
			Fouling	Sinking of farm		Conservative safety factors	3	1
		Wear	Friction with connected components due to slack in system	Loss of redundancy for whole farm	TRUE	Assure tension in system	2	4
		Elongation of headrope over time	permanent elongation of rope due to creep	Change in behaviour farm		Assure design tolerances to allow for dimensional varieties	3	1
10	Thimble connection failure	Overload	Erroneous load estimation	Loss of redundancy for whole farm	TRUE	Conservative safety factors	2	4
		Fatigue	Decreased strength caused by cyclic loading	Loss of redundancy for whole farm	TRUE	Conservative safety factors	2	4
		Wear	Friction with connected components due to play in system	Loss of redundancy for whole farm	TRUE	Conservative safety factors	2	3
		Degradation	Inherent degradation	Loss of redundancy for whole farm	TRUE	Conservative safety factors	2	4
		UV	UV exposure	Loss of redundancy for whole farm	TRUE	Conservative safety factors	2	4
		Fouling	Fouling	Loss of redundancy for whole farm		Conservative safety factors	3	1
		Installation errors	Improper fastening	Loss of redundancy for whole farm	TRUE	Hire contractors with domain expertise	2	4
11	Pipe failure	Buckling	Strength not sufficient to handle bending	Loss of redundancy for whole farm		Include redundant buoyancy	2	2

Appendix B: Risk map after mitigation

Proba bility	Likelihood	Consequence					
Class		1	2	3	4	5	6
6	Very high chance	•	•	•	•	•	•
5	High chance	•	•	•	•	•	•
4	Medium chance	•	• 1-Collision	•	•	•	•
3	Low chance	• 9-Headrope failure • 9-Headrope failure • 10-Thimble connection failure	•	• 3-Anchoring chain failure • 4-Mooring chain failure • 4-Mooring chain failure • 5-Mooring line failure • 6-Shackle failure • 6-Shackle failure	•	•	•
2	Very low chance	•	• 11-Pipe failure	• 1-Collision • 3-Anchoring chain failure • 3-Anchoring chain failure • 5-Mooring line failure • 6-Shackle failure • 7-Thimble connection failure • 7-Thimble connection failure • 7-Thimble connection failure • 10-Thimble connection failure	• 1-General component failure • 1-General component failure • 1-General component failure • 1-General component failure • 1-General component failure • 1-General component failure • 1-General component failure • 1-General component failure • 1-General component failure • 1-General component failure • 1-Contact of boat with anchoring system • 1-Contact of boat with anchoring system • 2-Mini pile failure • 2-Mini pile failure • 2-Mini pile failure • 2-Mini pile failure • 3-Anchoring chain failure • 4-Mooring chain failure • 4-Mooring chain failure • 5-Mooring line failure • 5-Mooring line failure • 5-Mooring line failure • 5-Mooring line failure • 6-Shackle failure • 6-Shackle failure • 7-Thimble connection failure • 7-Thimble connection failure • 8-Catenary buoy failure • 8-Catenary buoy failure • 8-Catenary buoy failure • 8-Catenary buoy failure • 8-Catenary buoy failure • 8-Catenary buoy failure • 8-Catenary buoy failure • 8-Catenary buoy failure	•	•

					• 9-Headrope failure • 9-Headrope failure • 9-Headrope failure • 9-Headrope failure • 9-Headrope failure • 9-Headrope failure • 10-Thimble connection failure • 10-Thimble connection failure • 10-Thimble connection failure • 10-Thimble connection failure • 10-Thimble connection failure		
1	Extremely low chance	•	•	• 1-Collision • 2-Mini pile failure • 2-Mini pile failure • 4-Mooring chain failure	• 1-Collision • 1-General component failure • 1-General component failure • 1-General component failure • 1-General component failure • 1-Contact of boat with anchoring system • 1-Contact of boat with anchoring system • 2-Mini pile failure • 2-Mini pile failure • 3-Anchoring chain failure • 5-Mooring line failure • 7-Thimble connection failure • 8-Catenary buoy failure • 8-Catenary buoy failure	• 2-Mini pile failure • 2-Mini pile failure • 3-Anchoring chain failure • 8-Catenary buoy failure • 8-Catenary buoy failure	• 2-Mini pile failure • 3-Anchoring chain failure

Key

- (red) High risk (unacceptable, measures shall be implemented)
- (yellow) Medium risk (measures shall be considered)
- (green) Low risk (no measures necessary)

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