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Report

AkvaLab – Project Summary Report

Evaluation of seaweed cultivation technology for weather exposed locations

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ABSTRACT
SINTEF Ocean has been hired by Vindel AS to give support and recommendations for establishing criteria for testing and evaluation of seaweed cultivation technology for weather exposed locations.

The project targeted the following secondary goals:
- Identification of relevant seaweed farm concepts for exposed areas.
- Identification of technological challenges and improvement needs for offshore seaweed farms.
- Contribute to testing and evaluation of a pilot concept.
- Contribute to building the foundation for a permanent research infrastructure.

The project has been executed in close cooperation with the Tareal 2 project.

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SINTEF

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Summary

SINTEF Ocean has been hired by Vindel AS to give support and recommendations for establishing criteria for testing and evaluation of cultivation technology in exposed areas.

The project targeted the following secondary goals:

- Identification of relevant seaweed farm concepts for exposed areas
- Identification of technological challenges and improvement needs for offshore seaweed farms
- Contribute to testing and evaluation of a pilot concept
- Contribute to building the foundation for a permanent research infrastructure

SINTEF Ocean was requested to review a new cultivation rig concept developed by the company Proaqua AS. The cultivation rig is called the "Proaqua rig". The results from this work concluded that the cultivation rig would not function as intended. This necessitated development, design and construction of an alternative test rig for technology evaluation. The test rig was also used for the cultivation tests in the Tareal 2 project.

The concept for the test rig was selected based on an evaluation of alternative seaweed farm concepts. A concept with vertical cultivation ropes, similar to the Macroalgal Cultivation Rig (MACR) designed by Ocean Rainforest was used for further evaluation and testing. One of the advantages with this concept is that the rig partly enters into a "survival mode" in rough weather conditions, by allowing the smaller buoys attached to each cultivation rope to submerge due to the tension in the cultivation ropes. This effect reduces the total hydrodynamic loads, which means the seaweed farms could be designed with fewer and smaller anchors and reduced rope dimensions compared to seaweed farm concepts with horizontal ropes.

The project has also evaluated required instrumentation for technology evaluation and for future seaweed farms in operation. Further, the design requirements and the required safety levels in design of seaweed farms are discussed. Finally, technological challenges and future improvement needs are identified.

The project has been executed in close cooperation with the Tareal 2 project, headed by Jorunn Skjermo (SINTEF Ocean), in good cooperation with the customer Vindel AS, represented by Asgeir Bahre Hansen, Siri Aarland and project manager Nils Erik Pettersen (aPoint) and with good support from the county authorities of Møre and Romsdal, represented by Rebecca Varne and Bengt Endreseth. Vindel AS prepared the input to Sections 7.4 and 7.5 of the report.

1 Introduction

SINTEF Ocean has, on behalf of the county authorities of Møre and Romsdal, made a report (Broch et al., 2016) on the potential for large scale macroalgal cultivation in Møre and Romsdal county (project Tareal 1). The report shows that the conditions for macroalgae cultivation are favourable in exposed areas along the Norwegian coast and at open sea.

As a continuation of this work, the county authorities of Møre and Romsdal assigned a new project to SINTEF Ocean, project Tareal 2, where the main purpose was to partly be able to verify the theoretical cultivation potential identified in Tareal 1, by performing cultivation tests in exposed areas.

Further, the county authorities of Møre and Romsdal, aims to contribute to knowledge building and development of technology for macroalgae cultivation in exposed areas. Vindel AS received funding from the county authorities for the project Akvalab. The main goal of this project has been to establish an offshore test location for testing of cultivation technology and to build the foundation for a permanent research infrastructure. SINTEF Ocean was hired by Vindel to support the project in establishing criteria for testing and evaluation of cultivation technology in exposed areas. The project has been executed in close cooperation with the Tareal 2 project.

The project targeted the following secondary goals:

- Identification of relevant cultivation technology for exposed areas
- Identification of technological challenges and improvement needs for offshore seaweed farms
- Contribute to testing and evaluation of a pilot concept
- Contribute to building the foundation for a permanent research infrastructure

Achievement of the main and secondary goals will give increased knowledge on technology for macroalgal cultivation in exposed areas. This may contribute to realising the potential for large scale macroalgal cultivation in Møre and Romsdal county.

1.1 Tareal 2 project summary

In the winter of 2020 (1st of February), the test rig (Appendix G) was installed at Klovningen (Appendix C) and cultivation ropes with seedlings was deployed. At the same time, a similar test rig with cultivation ropes was installed at Orstranda in Freifjorden.

Measurements of seaweed growth in 2020 was recorded 23rd of April, 19th of May and 8th and 12th of July (at Orstranda and Klovningen respectively). These measurements showed a biomass growth at Orstranda from 0.9 kg/m in April to 5 kg/m in June, and at Klovningen a growth from 0.3 kg/m in April to 3.5 kg/m in June. These are average measurements for 5 and 4 ropes at Orstranda and Klovningen respectively. At Klovningen it was measured 5,8 kg/m on two of the ropes and only 0,24 kg/m for the poorest rope. The large variation in biomass growth at Klovningen is assumed to be caused by a partial breakdown of the cultivation rig, due to loss of a mooring buoy, causing loss of one cultivation rope and that 3 of the ropes were temporarily left too deeply submerged until 23rd of April. The biomass growth was largest in the period from 19th of May to 8th - 12th of June. In this period the biomass at Orstranda doubled and at Klovningen the biomass increased sevenfold. Figure 1 shows a cultivation rope at Klovningen at 23rd of April and at 12th of June (Skjermo et al., 2020).

Figure 1: Cultivation ropes at Klovningen 23rd of April and 12th of July (Photo: SINTEF Ocean)

2 Identification of relevant seaweed farm concepts

2.1 Seaweed farms in Norway and northern Europe

The general layout and design of the seaweed farms used by some of the leading seaweed cultivation companies in Norway, Seaweed AS, Ocean Forest AS and Seaweed Energy Solutions AS, are all based on horizontal cultivation ropes attached to a mooring grid system. The concepts are based on "endless" cultivation ropes that are attached to the load carrying ropes in the mooring grid system and the cultivation ropes are attached/removed during seeding/harvesting.

The mooring grid system is left in place after ending the harvesting season and may be re-used for several years. The moorings and the mooring grid systems are based on similar layout and components as used for aquaculture fish farms (Figure 2). The existing Norwegian seaweed farms are relatively small, typically 1-3 hectare, and are placed in sheltered waters.

Ocean Rainforest at the Faroe Islands uses a different concept with vertical cultivation ropes. Seaweed farm concepts based on two-dimensional cultivation substrates, such as nets, canvas or ribbons are also commercially available, but these are rarely used in Norway.

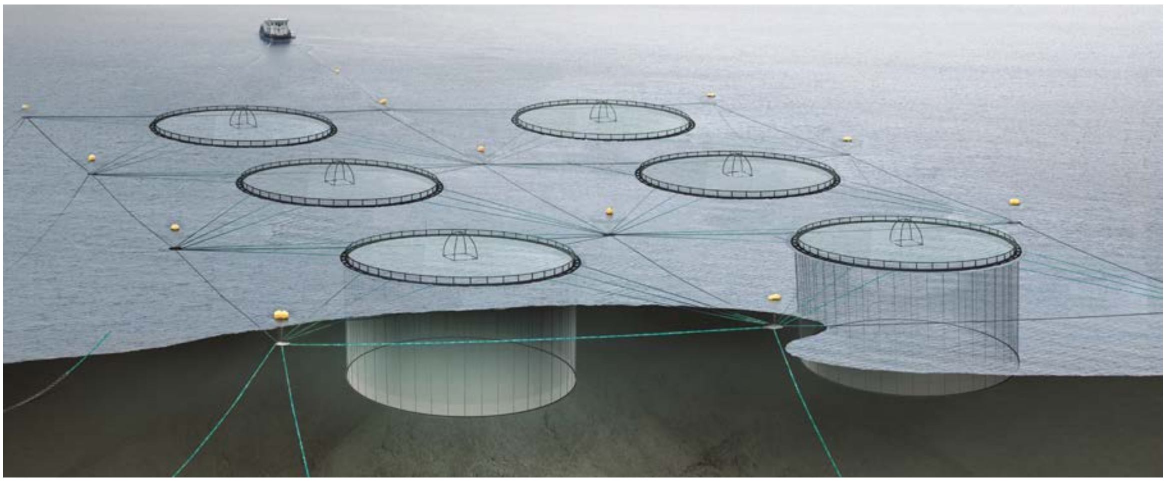

Figure 2: Typical mooring grid configuration used for fish farms (Figure: Akva Group)

2.1.1 Værlandet fiskeredskap – Buland 10

"Buland 10" is a commercially available seaweed farm concept from the vendor Værlandet Fiskeredskap AS. As the trade name indicates, the size of this sea farm is 10 decare (1 hectare) (Figure 3). This concept is used by the seaweed cultivation company Seaweed AS at Værlandet (Vestland county).

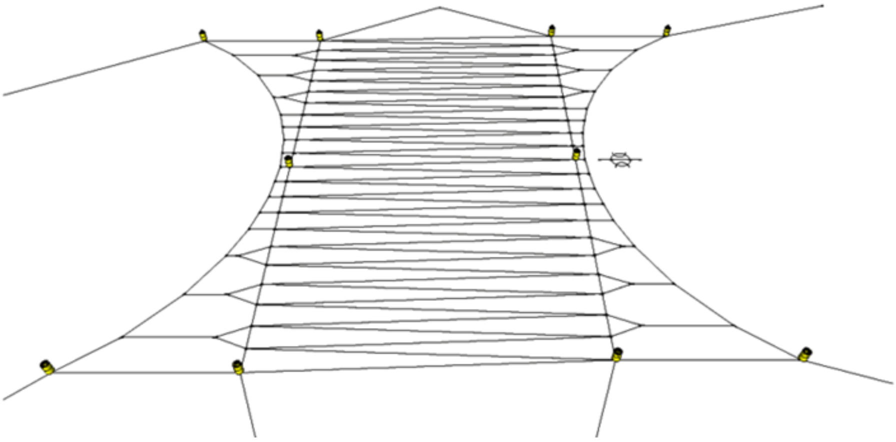

Figure 3: "Buland 10" - commercially available seaweed farm concept (Figure: Værlandet Fiskeredskap AS)

2.1.2 Ocean Forest

Ocean Forest uses a "standard" mooring grid where the size of each sea farm typically measures 75 x 150m (Figure 4) (Ocean Forest, 2017). To avoid that the cultivation ropes and the seaweeds are intertwined due to the wedge shape created by the ropes in the "Buland 10" concept, the layout of the cultivation ropes are rectangular in this concept. The cultivation ropes are typically 14 mm polypropylene or similar material.

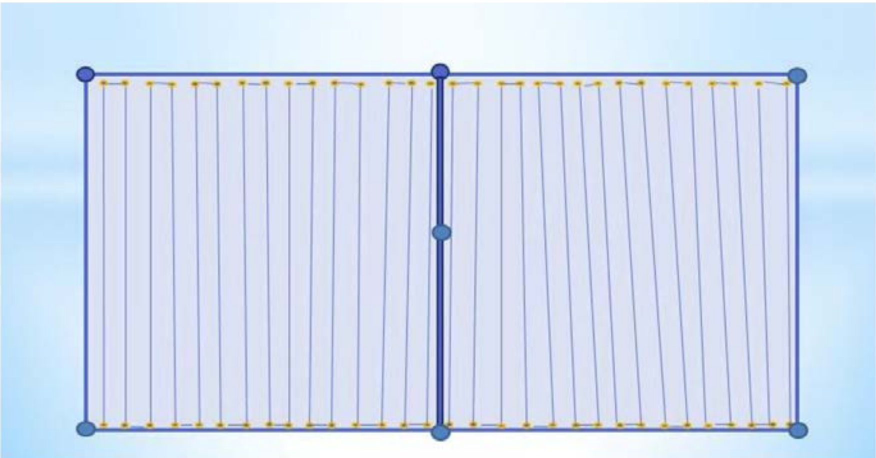

Figure 4: Sketch showing Ocean Forest's seaweed farm concept (Ocean Forest, 2017)

2.1.3 Seaweed Energy Solutions (SES)

Seaweed Energy Solutions' (SES) sea farm typically covers an area of 3 hectare (Berggren, 2019).
SES uses a method of direct seeding on ropes in hatchery, meaning that the cultivation ropes are thinner, typically 6 mm, to reduce space requirements in the hatchery. Thinner ropes have less load capacity and hence the span between the load carrying ropes in the mooring grid needs to be shorter. SES are using a span of approximately 14 meter in their farm (Berggren, 2019).

2.1.4 The Macroalgal Cultivation Rig (MACR) – Ocean Rainforest

Ocean Rainforest at the Faroe Islands uses a concept with vertical cultivation ropes (Figure 5) (Bak et al., 2018). This concept is assumed to reduce the hydrodynamic loading in harsh weather conditions, since the cultivation ropes are allowed to move along with the waves. In large waves the small buoys attached to each cultivation rope will submerge and hence the loading on each cultivation rope and the total loading on the rig may be reduced compared to a rig with fixed cultivation ropes. The concept has been successfully tested in significant wave heights (H_s) up to 4 meters and in currents up to 3 knots at the Faroe Islands (Bak, 2019).

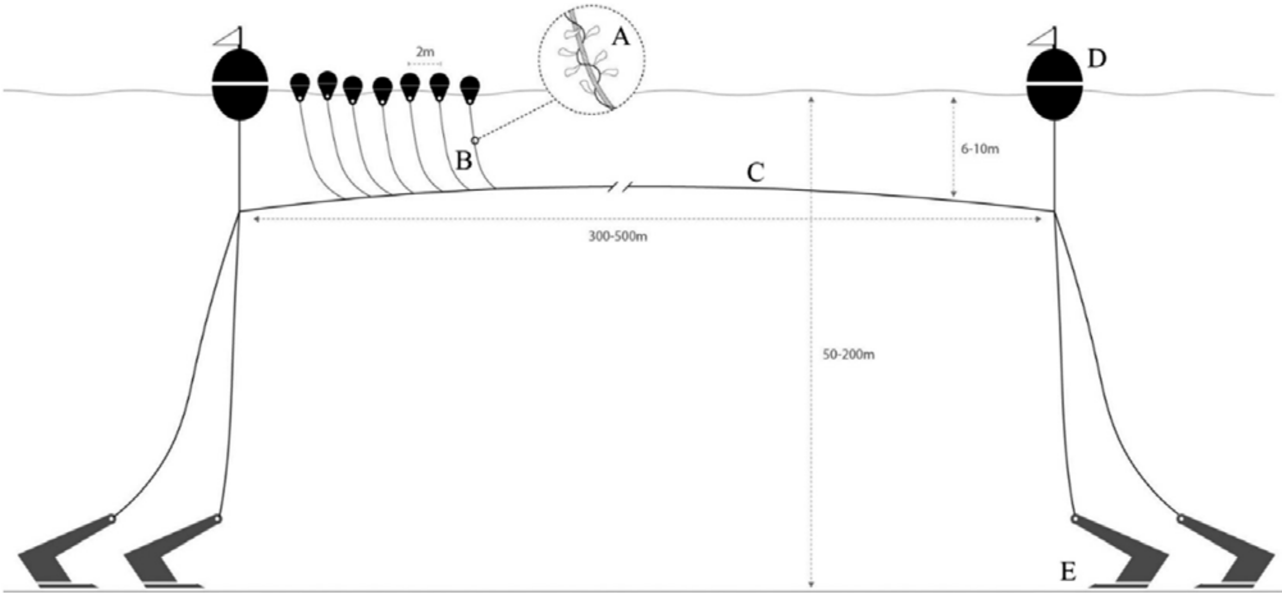

Figure 5: Schematic drawing of a Macroalgal Cultivation Rig (MACR) by Ocean Rainforest

2.2 2D-based substrate systems

Seaweed farm concepts based on two-dimensional cultivation substrates, such as nets, canvas or ribbons are commercially available. These concepts are rarely used in Norway, but they are more frequently used in the southern parts of the North Sea.

2.2.1 AtSeaNova

The company AtSeaNova, located in Belgium, is producing and marketing different concepts based on two-dimensional substrates. Their main product consists of a 2m x 10m canvas that could be assembled into desired lengths (Figure 6). The canvas may experience large hydrodynamic loads in waves and currents due to its large surface area. To deal with this, AtSeaNova also has ribbons down to 5 cm width. Nets (similar to Figure 7) could also be used in their seaweed farm concepts.

Figure 6: AtSeaNova – canvas cultivation substrate (Picture: AtSeaNova)

2.2.2 SmartFarm

Smart farm is a concept for cultivation of mussels that uses flexible pipes as buoyancy elements for net based cultivation substrates. The concept could in theory also be used for seaweed cultivation. A mechanized harvesting machine for mussel, that moves along the flexible pipes has been developed (Figure 7).

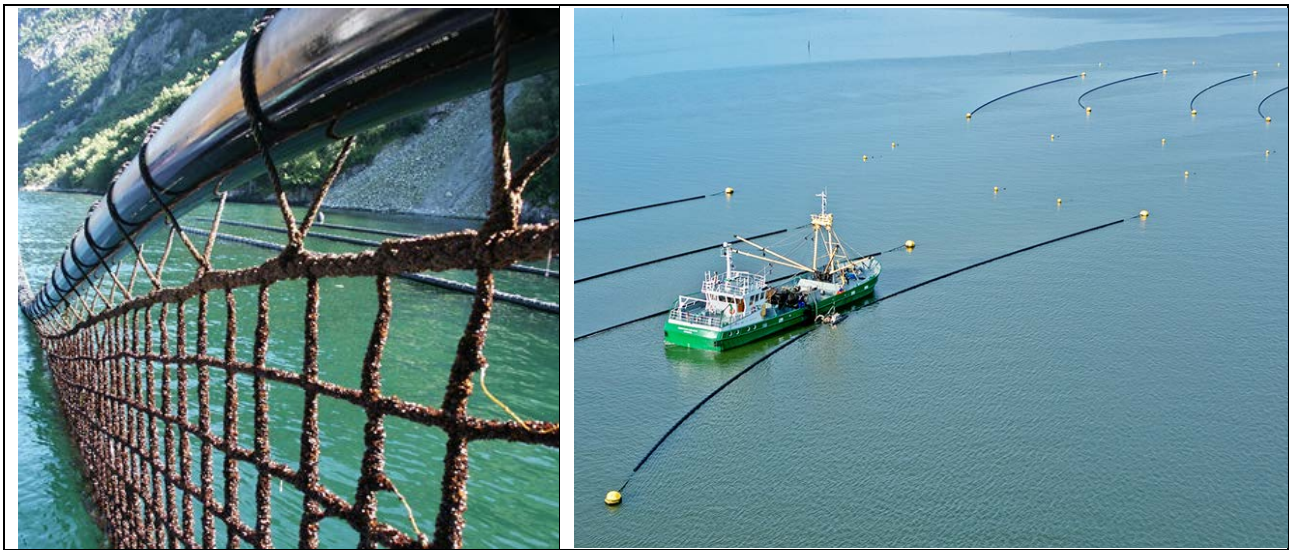

Figure 7 SmartFarm – net for cultivation of mussels (left) and sea farms and harvesting equipment (right) (Pictures: SmartFarm)

2.3 Sea farms in Asia

Seaweed farms in Asia are mainly based on ropes or nets as cultivation substrate, depending on the cultivated species.

2.3.1 Net for cultivation of Porphyra (Nori)

Nets are used for cultivation of *Porphyra* (Nori) (Figure 8). China, South Korea and Japan are the largest producers of *Porphyra* (FAO, 2018). The total production volume of *Porphyra* only amounts to 1.4 million tonnes wet weight of a total global production volume of 30 million tonnes. However, in terms of value, *Porphyra* is considered the most valuable maricultured seaweed in the world (FAO, 2018).

Figure 8: Cultivation of Porphyra in Japan. From (Pereira and Yarish, 2008)

2.3.2 Cultivation on ropes

Saccharina japonica (kelp) is the dominating species for rope cultivation in China. China is by far the largest producer of *S. japonica* with a global production of 7 million tonnes (FAO, 2018) Cultivation is traditionally done on ropes (Figure 9). Sea farms are located both offshore and inside gulfs/bays. Today, the offshore farms are made of modern equipment such as nylon ropes and plastic floats. The nearshore sea farms use cheap foam or leather materials as floats (Alver et al., 2018, Pereira and Yarish, 2008, Zhang, 2018).

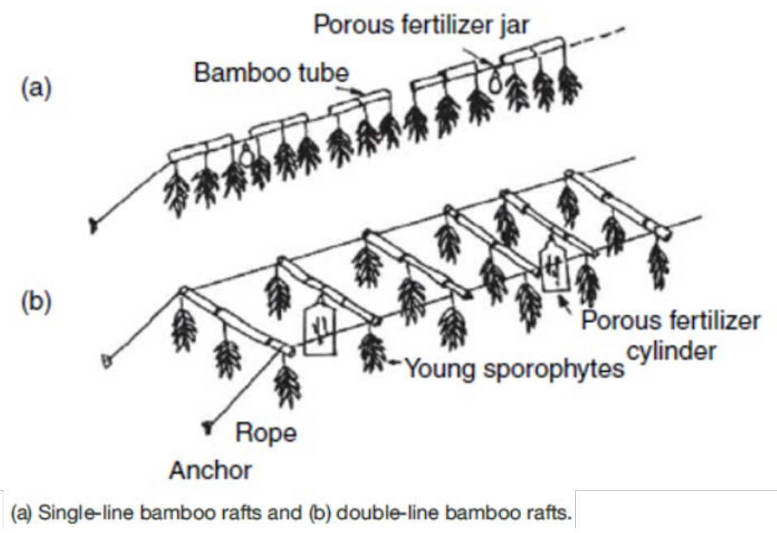

Figure 9: Traditional concept for rope cultivation in China. From (Pereira and Yarish, 2008)

2.4 Methods for harvesting of seaweed

2.4.1 Norway

Existing seaweed farms and harvesting methods involves a lot of manual work, which is time consuming, physically demanding and may compromise personal safety. This leads to low profitability for Norwegian seaweed farmers. Development of seaweed farms and specialised cultivation vessels that could handle large volumes at low operating costs, by offering increased level of automation and mechanisation, are assumed to play an important role in the development of a future seaweed industry in Norway.

Today, service vessels from the aquaculture industry or small fishing vessels are used for harvesting. The cultivation rope is normally pulled in by a winch located at the deck of the vessel. The vessels crane tip is placed above the storage trays and the seaweed peels off the cultivation rope as the rope passes through a ring or shackle attached to the crane tip (Figure 10).

The cultivation ropes are detached from the mooring grid by using smaller boats operating inside the seaweed farm. The cultivation ropes are normally at 0,5 m to 1,0 m depth and need to be lifted manually out of the water before being disconnected from the load carrying rope. This work is physically demanding, may compromise personal safety and is labour intensive. There is a great potential in making this part of the operation more efficient.

Figure 10: Ocean Forest - harvesting method (Picture: snapshot from Youtube)

2.4.2 China

Seaweed production in China accounts for 47% of the global production volume of cultivated seaweeds (FAO, 2018). In China, deployment and harvesting is done manually, requiring much manpower and there is a large demand for seasonal workers. Almost no mechanized harvesting equipment is used, and a knife is more or less the only available tool. Workers cut the cultivated kelp rope and lift the kelp together with the rope onto the boat (Alver et al., 2018, Zhang, 2018). There have been some attempts to develop mechanized harvesting machines designed for the traditional floating raft seaweed farms (Figure 11). However, the kelp ropes are still detached from the longitudinal raft ropes by hand, as the machine does not offer any automation of removing the kelp from the kelp ropes (Alver et al., 2018).

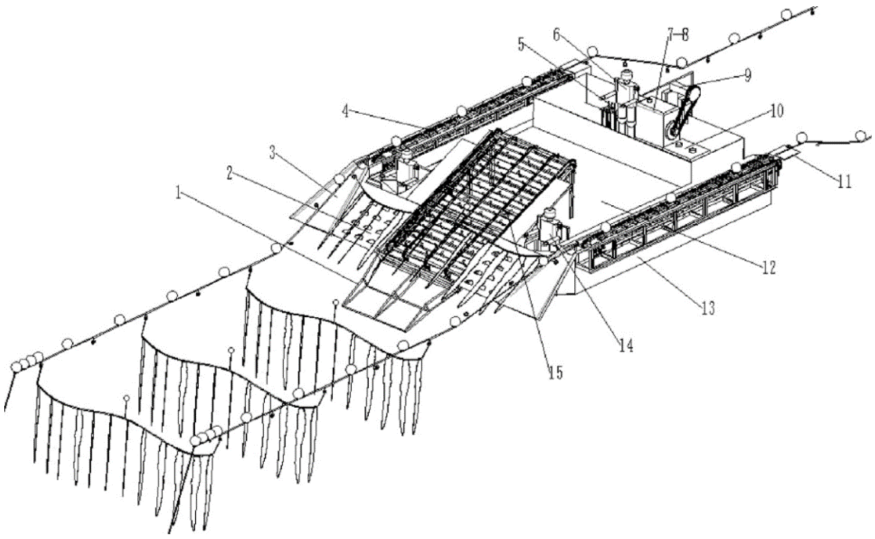

Figure 11: Mechanized harvesting machine. From (Zhang et al., 2017)

2.4.3 Seaweed Cultivation Vessel 2020

Specialised cultivation vessels that could handle large volumes at low operating costs are assumed to play an important role in the development of a future seaweed industry in Norway.

In the innovation project "Seaweed Cultivation Vessel 2020" (2017-2020), funded by the Research Council of Norway, a vessel concept for industrial seaweed cultivation has been developed (Figure 12). The vessel will serve all stages of seaweed cultivation, including i) installation of seaweed farms, ii) transport and deployment of seedlings, and iii) harvest and transport of fully-grown seaweeds.

The total concept consists of three different vessel concepts with different harvest- and storage capacity for stepwise introduction into a growing seaweed industry. The vessel concepts are based on a combination of existing vessel types, such as 1) service vessels for aquaculture industry and 2) seaweed harvesters, and 3) a new vessel concept, which may also serve the aquaculture industry. For all vessel concepts, the harvesting-, handling-, storing and preservation equipment will be modular to allow for alternative use of the vessels in the off-season. Whereas concept 1) and 2) primarily will operate inshore, concept 3) is also designed to operate offshore, both because the growth conditions are more favourable, but also in order to reduce potential area conflicts in the coastal zone.

A high degree of mechanisation and automation in handling and processing of the seaweed ensures efficient operations, high product quality and safety for personnel (https://taredyrkingsfartoy2020.no/).

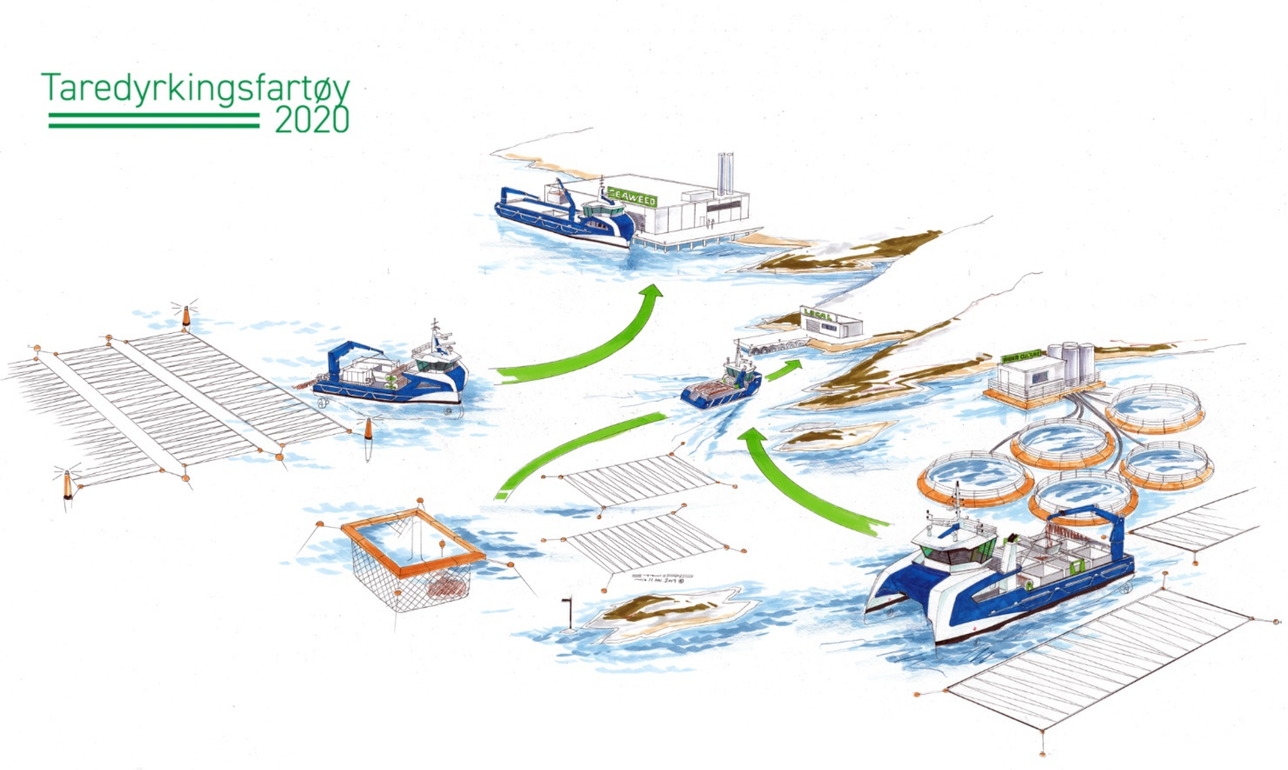

Figure 12: Seaweed Cultivation Vessel 2020 (Figure: Thorup Design AS / Taredyrkingsfartøy2020)

2.5 Other novel seaweed farm concepts

2.5.1 Seaweed Energy Solutions – Seaweed Carrier

Seaweed Energy Solutions (SES) has a patented concept for a cultivation rig called the "Seaweed carrier" (Figure 13). The concept is based on a two-dimensional structure connected to a single point mooring, which allows the rig to align with the dominating weather direction. It has been tested in small scale, but it has not been used for commercial production. The concept is designed for rough weather conditions. Any information on how mechanised and efficient harvesting from these cultivation rigs should be performed has not been found.

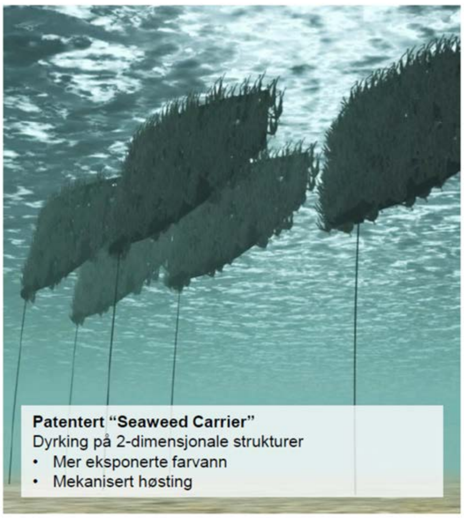

Figure 13: Patented, not commercialized concept, "Seaweed Carrier" (Pictures: Seaweed Solutions)

2.5.2 MACROSEA – SPOKe (Standardized Production of Kelp)

In the MACROSEA project, a desktop study has been performed for the development of an area-efficient concept for seaweed cultivation, that allows for a high degree of automation (Figure 14). The concept is based on a high degree of standardization, which makes it possible to utilize an advanced harvesting robot and to transfer this robot between different seaweed farms (Bale, 2017).

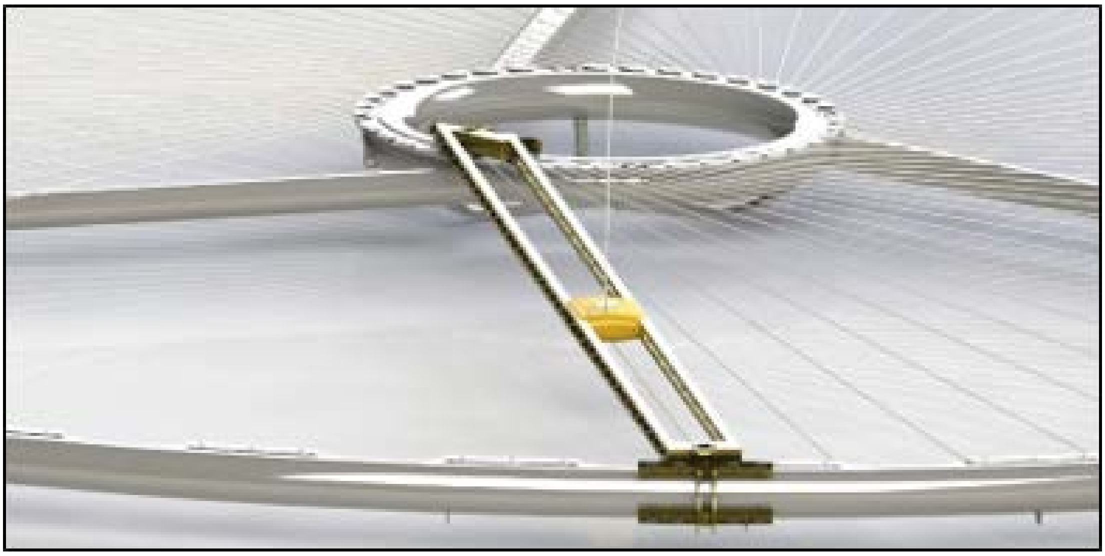

Figure 14: MACROSEA – SPOKe – høsterobot. From (Bale, 2017)

2.6 Existing seaweed farm concepts - summary

Seaweed farms for scaled seaweed cultivation do not exist in Norway. The existing Norwegian seaweed farms are small scale and require a lot of manual work operations, which will not be cost-efficient for large scale production. Increased level of mechanisation and automation in handling and processing of the seaweed is required to increase efficiency and safety of operations. There is a potential for scaling up the existing seaweed farm concepts in Norway if a cost-efficient and robust method for connecting and disconnecting the cultivation ropes to the mooring grids is developed.

The existing seaweed farms in Asia are truly large scale, but almost no mechanized equipment is used in deployment or harvesting of seaweed, which makes the operations very labour intensive.

The existing Norwegian seaweed farms are placed in sheltered waters. The semi-rigid arrangement of these seaweed farm concepts, with tensioned cultivation ropes in the most wave affected zone, makes these concepts unsuitable at more exposed locations. The cultivation rig used by Ocean Rainforest, with vertical cultivation ropes, has been demonstrated for rough weather conditions. It should be further investigated how this concept could be used for scaled seaweed production and how to mechanize the harvesting process. Alternative seaweed farm concepts for weather exposed locations should also be further investigated.

3 Design criteria for seaweed farms

3.1 Design standard for seaweed farms

Existing Norwegian seaweed farms are relatively small, typically 1-3 hectare, and are placed in sheltered waters. There is no specific standard that sets requirements for design of seaweed farms. In lack of a specific standard for seaweed farms, it is common practice to adopt relevant requirements from the governing standard for fish farms, NS9415:2009, "Marine fish farms - Requirements for design, dimensioning, production, installation and operation" (Norsk Standard, 2009). The purpose of this standard is to reduce the risk of escape as a result of technical failure and wrong use of marine fish farms.

The different standards for structural design in various industries have different target levels of safety based on the possible consequences of structural failure. In Europe, the Load and Resistance Factor Design (LRFD) method is the preferred method for structural design and this method is also enforced by the Eurocodes. NS9415:2009, also uses the LRFD method for structural design, which implies that the target safety level is obtained by multiplying or dividing characteristic values of loads and structural (or material) resistance by deterministic load and material factors (DNV GL, 2015). In other words, load factors are applied to the estimated characteristic environmental loads and material factors are applied to the various structural components to obtain the desired safety level.

For the design of seaweed farms, a future design standard could consider applying a lower safety level than for fish farms. First of all, the consequences of technical failures are significantly lower for a seaweed farm, compared to a fish farm where the main risk is escape of fish. Secondly, most fish farms are also manned on a daily basis, which means that structural failures also impose a risk for injury to personnel. Finally, the period for maximum biomass in the seaweed farms (typically spring) is also most likely outside the window for when the maximum environmental loads occur (typically late autumn/early winter). This may justify use of reduced load- and material factors for design of seaweed farms compared to design of fish farms. Reduced conservatism will contribute to more cost-efficient design of seaweed farms.

3.2 Other requirements

Seaweed farms need to be marked according to the Norwegian Coastal Administration's requirements for marking of aquaculture sea farms. The relevant legislation is "Kystverkets forskrift av 19. desember 2012 nr. 1329 - Forskrift om farvannsskilt og navigasjonsinnretninger" (Samferdselsdepartementet, 2013).

4 Evaluation of proposed pilot cultivation rig from Proaqua

SINTEF Ocean was requested to review a new cultivation rig concept developed by the company Proaqua AS. The cultivation rig is called the "Proaqua rig" (Figure 15 and Figure 16). Proaqua specifically needed assistance on:

1) estimating the required size of the anchor (single point mooring),
2) estimating the required size of the buoyancy elements and,
3) how changing the depth of the cultivation mat affects the loads on the rig.

The customer, Vindel AS, also requested SINTEF Ocean to evaluate if the cultivation rig was suitable for the intended cultivation site at Klovningen, a weather exposed location in the Grip archipelago outside Kristiansund.

4.1 Description of the Proaqua rig

The main elements of the concept are a large plastic ring that supports a cultivation mat and the floater/mooring system consisting of 4 buoyancy elements and 4 mooring lines, which are connected via a swivel to a single point mooring. The ring and the cultivation mat are close to neutrally buoyant and are balanced by two smaller buoyancy elements. The mooring lines are weighted to maintain the mooring line catenary. A flap/spoiler is attached to a sector of the ring to rotate the cultivation mat in a favourable position. Figure 15 shows the structural elements of the rig and Figure 16 also shows the cultivation mat, the flap/spoiler and the two smaller buoyancy elements.

The idea of the concept is that the mooring lines attached to each of the four main buoyancy elements are allowed to move freely in vertical direction through frictionless brackets on the ring. This means that any movements of the buoyancy elements should not impose vertical movements of the ring and the cultivation mat. Further, the ring should be restricted from sideways movements due to tension and the catenary configuration of the mooring lines, provided by the weighted mooring lines. The plastic ring is equipped with a flap/spoiler that should rotate the cultivation mat in a favourable position that causes minimum loading on the rig. Since the ring and the cultivation mat are close to neutrally buoyant, it should be easy to hoist it to the surface for inspection and harvesting.

4.2 Scope of work

Proaqua needed assistance on estimating the required size of the anchor (single point mooring) and the required size of the buoyancy elements. This implies a calculation of the global dimensioning forces on the cultivation rig to give an estimate of the tension in the mooring and anchor lines. Further, the tension in the anchor line could be used to give a recommendation for required anchor size. No assessment of local forces in the various structural components was performed.

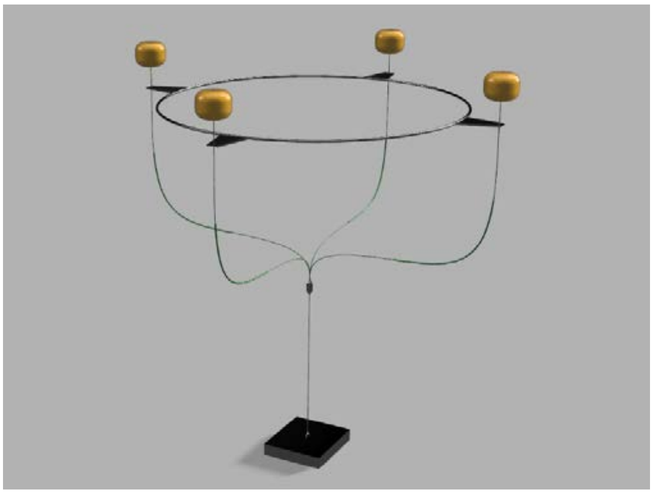

Figure 15: CAD drawing of "Proaqua rig" (from Proaqua)

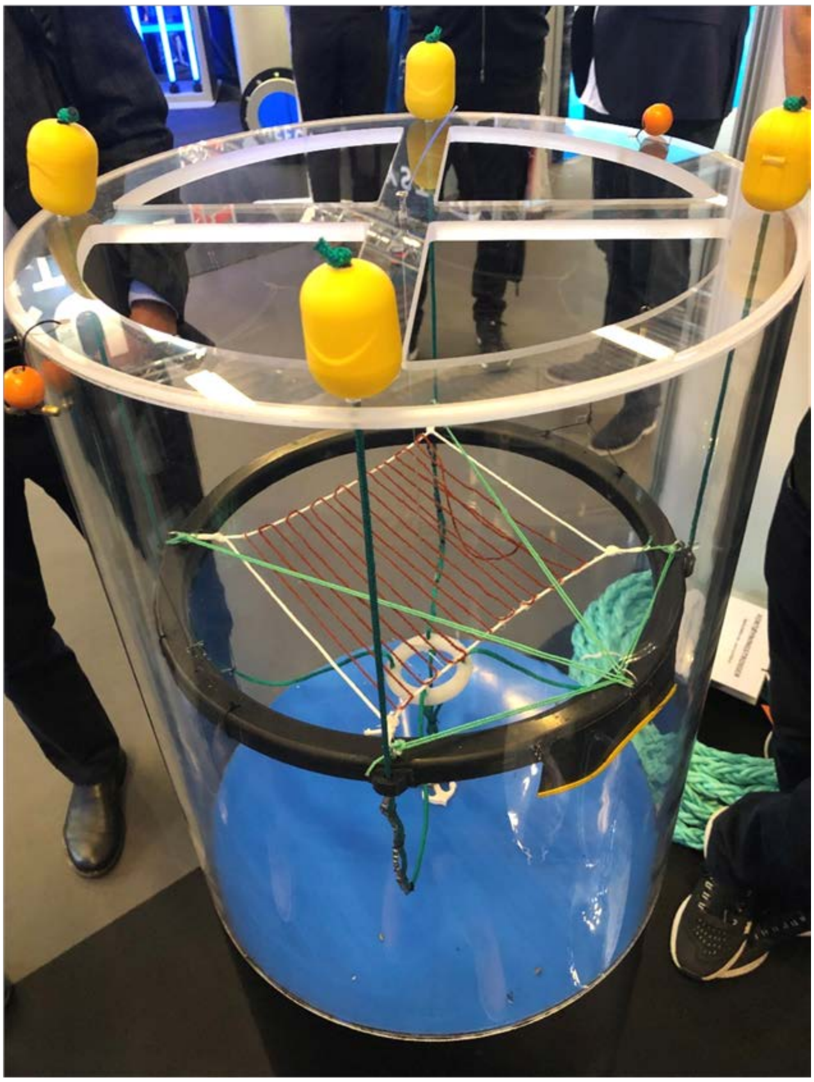

Figure 16: Model of Proaqua seaweed rig system – "Proaqua rig"

4.3 Input parameters

Input parameters for the calculations such as dimensions, weights and material properties were collected from hand sketches (Figure 17) and additional information provided by Proaqua. Details are included in Appendix A.

For these calculations, a current velocity of 0,7 m/s was used. The concept "failed" before wave forces were applied, hence no estimate for maximum dimensioning wave height was used for these calculations.

The methods for applying environmental loads, selecting relevant load combinations and estimation of load effects follows the principles described in 6.3 and 0.

The plastic ring is equipped with a flap/spoiler that should rotate the cultivation mat in a favourable position in such a way that the main current and wave forces are acting in parallel with the cultivation ropes. This will reduce the global loads on the rig. In accordance with recognised design standards, possible failure modes need to be considered in the design. Possible entanglement and/or insufficient weighting of this flap may cause it to malfunction. This means that a load case where the forces are acting perpendicular to the cultivation ropes needs to be considered. This load case may, however, be treated as an accidental load case, with reduced load factor, i.e. load factor 1.0 according to NS9415.

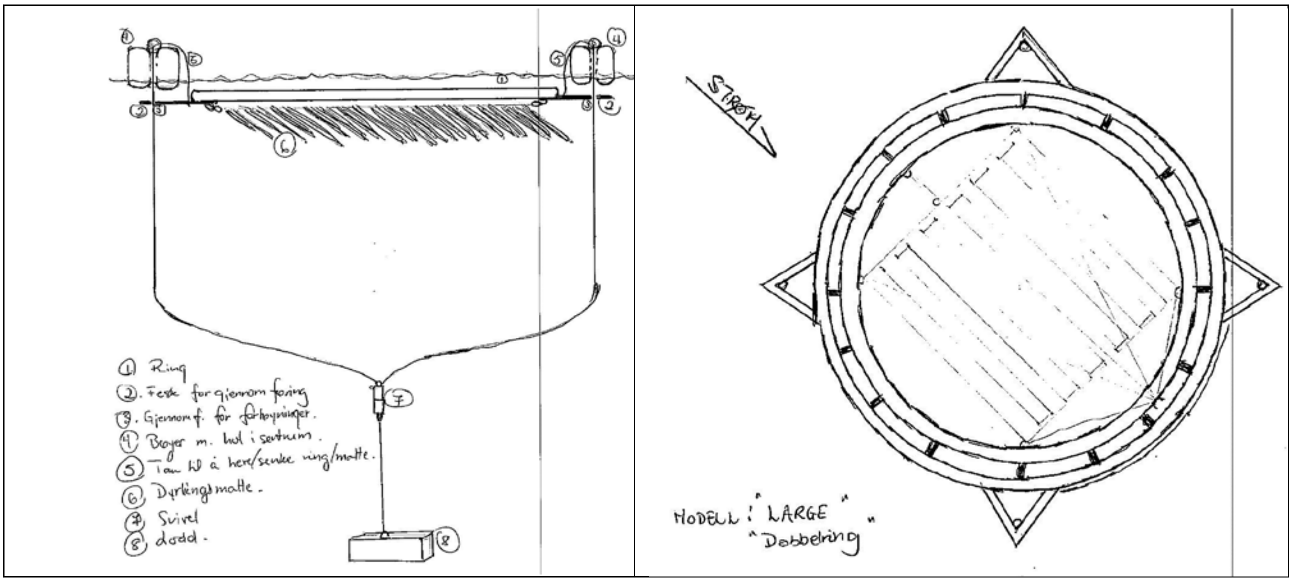

Figure 17: Sketch of "Proaqua rig" - side view and top view (from Proaqua)

All analyses were carried out using FhSim. FhSim is a software platform and framework for mathematical modelling and numerical simulation, with a focus on marine applications FhSim is developed by SINTEF Ocean (SINTEF Ocean, u.d.). The software also features 3D visualization.

4.4 Results

Details of the analyses performed in the simulation programme FhSim are included in Appendix A. A summary of the results from the analyses are included below.

The simulation results show that the cultivation rig will not function as intended. When currents are acting on the rig, the rig will move along with the current. The two mooring lines facing downstream will be tensioned and fully taut, whereas the two mooring lines facing upstream will be slack. The ring with the cultivation mat, which is close to neutrally buoyant, will be pushed along the mooring lines towards the surface. In bad weather conditions/strong current, the tension in the downstream facing mooring lines will start to pull the mooring buoys down, causing the ring with the cultivation mat to tilt and act as a large sail, which will further increase the mooring line loads (Figure 18). This means that in bad weather conditions, the rig tends to seek towards a position/configuration where even worse conditions are experienced.

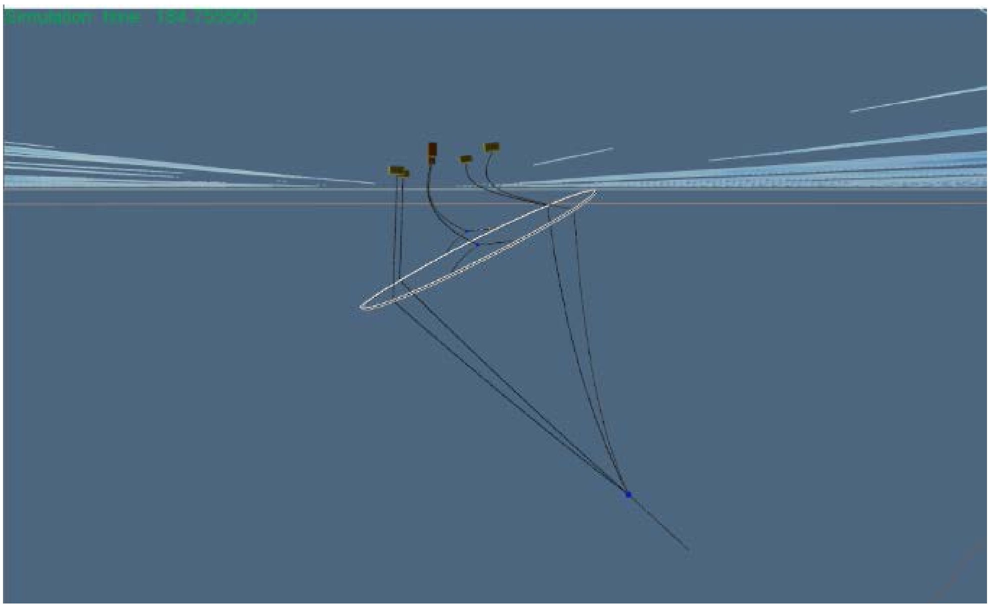

Figure 18: FhSim - visualisation of results – Proaqua rig in strong current

4.5 Evaluation of pilot cultivation rig from Proaqua - conclusion

The simulations show that in strong currents, without any wave forces applied, the ring with the cultivation mat will be pushed towards the surface. At the same time, the rig is not stable and will not maintain a horizontal position, which may further increase the loads on the rig and lead to unacceptable loads on the mooring and anchor lines.

The possibilities for improving the existing concept are limited, for reasons as explained below:

1) To keep the ring with the cultivation mat in position, the weight of the ring needs to be increased significantly. The two smaller buoyancy elements, shown as orange buoys in (Figure 16), need to be significantly larger to balance this weight. This means that the ring with the cultivation mat will be directly exposed to the vertical motions of the waves acting on these buoyancy elements, which conflicts with the design philosophy of this concept.
2) The weighting of the ropes has a negligible effect on maintaining the mooring line catenaries, even if the weights are significantly increased compared to the planned weighting. It is not possible for the weighted ropes to maintain the upper part of the mooring lines in vertical position.
3) The ring with the cultivation mat could be locked at a desired depth to avoid that the ring is pulled towards the surface in strong currents. This would however increase the dynamic loads in waves and the static configuration, where the ring may tilt, would still occur.

Based on these findings, it was agreed with the client to not proceed with the Proaqua rig concept as a pilot concept for the project.

5 Evaluation of seaweed farm concepts

5.1 Evaluation model for seaweed farm concepts

A complete evaluation of a seaweed farm concept requires evaluation of several factors. In this project, where the technical solutions for offshore seaweed farm concepts are in focus, factors that contribute to robust and cost-effective operations in all phases of the seaweed farms life cycle should be considered. This should normally include evaluation of factors such as:

- Construction of the seaweed farm – cost of components and installation costs
- Seeding methods – possibilities for automation of seeding
- Operation – robustness, forces and motions in extreme weather conditions
- Surveillance and maintenance - possibilities for automation and remote monitoring
- Harvesting - possibilities for automation/and or cost-efficient harvesting
- Decommissioning – decommissioning costs and possibilities for re-use or recycling of components
- Safety – risk for loss of structural components and risks to marine traffic
- Environment – risk for discharge of microplastics or loss of structural components

A systematic approach for evaluation of seaweed farm concepts are described in (Berggren, 2018, Groenendijk et al., 2016). Due to changes in project scope, caused by the abandonment of the pilot rig for further evaluation and subsequent requirement for design of an alternative test rig, a systematic approach evaluation of seaweed farm designs was not further explored in this project. However, a simplified desktop evaluation of alternative seaweed farm concepts, focusing on the construction and operation phases, was performed.

5.2 Evaluation of alternative concepts

Two alternative concepts were selected for further evaluation. The concepts were selected based on currently available cultivation technology used in Norway and Northern Europe as described in Section 2.1:

1) a traditional mooring grid concept with horizontal cultivation ropes, based on the concepts shown in (Figure 2, Figure 3 and Figure 4), hereafter called the hLine (horisontal line) concept.
2) a concept with vertical cultivation ropes, similar to the Macroalgal Cultivation Rig (MACR) constructed by Ocean Rainforest (Figure 5), hereafter called vLine (vertical line) concept.

The desktop study mainly focused on the construction and operation phases, where the main selection criterion was evaluation of hydrodynamic loads. The concept that experiences the lowest hydrodynamic loads could be constructed by using fewer and smaller anchors, reduced rope dimensions and reduced size of other load bearing components. This will contribute to development of cost-efficient seaweed farms.

The two concepts were evaluated based on results from FhSim analyses, see Appendix B for details.

When using plough anchors, the angle of the mooring lines should be minimized to reduce vertical loading and subsequent unintended release of the anchors. The length of the anchor lines should normally be taken as minimum 3 times the water depth. This reduces the available length/area for the cultivation rig itself since the anchor lines also needs to be placed inside the available area. Both concepts were designed to fit inside the granted cultivation area at Klovningen.

The vLine concept consisted of 5 x 10 meters of cultivation rope at 0-10m depth using 4 anchors, whereas the hLine concept consisted of 6 x 33 m of cultivation ropes at 2 m depth using 8 anchors. Due to the difference in length of cultivation ropes, the results are not directly comparable, but the results indicate that the vLine concept experiences less hydrodynamic loads compared to the hLine concept. This means that by using the vLine concept the seaweed farms may be designed with fewer and smaller anchors and reduced rope dimensions compared to a hLine concept. As seen in (Figure 19), the test rig partly enters into a "survival mode" in rough weather conditions, by allowing the smaller buoys attached to each cultivation rope to submerge due to the tension in the cultivation ropes. This effect reduces the total hydrodynamic loads.

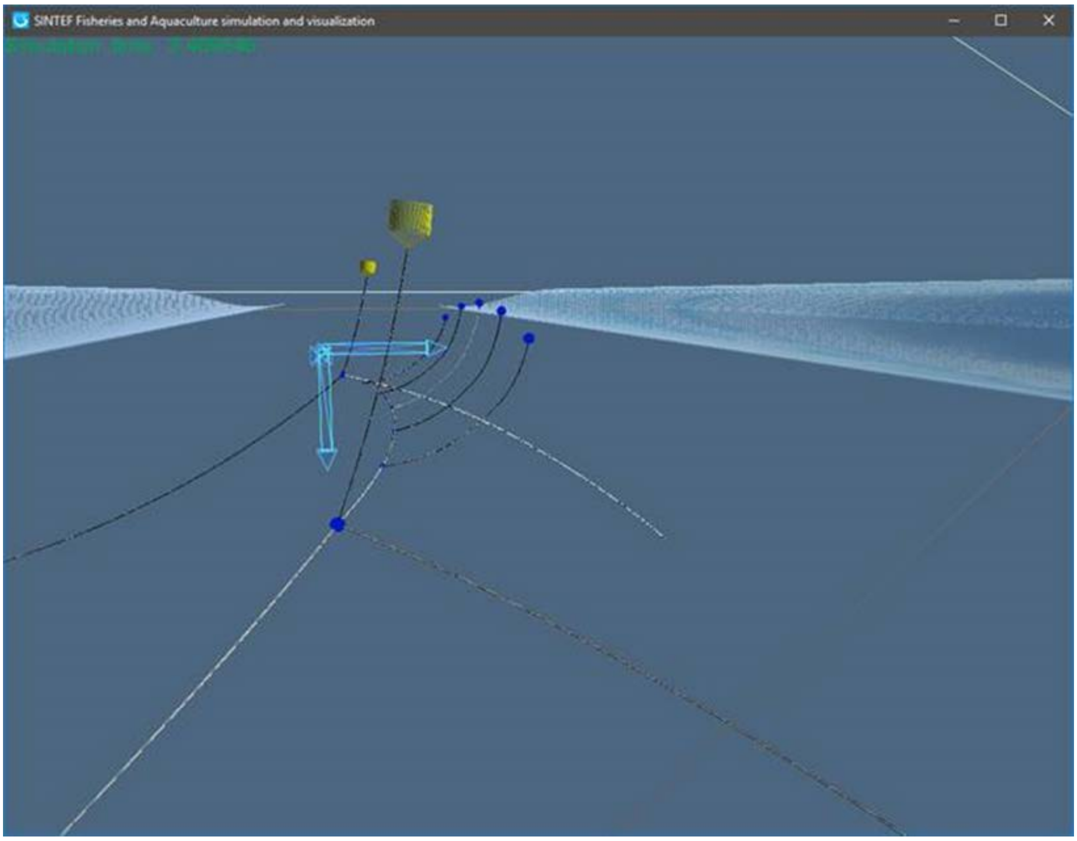

Figure 19: vLine concept in extreme wave condition

5.3 Identification of required instrumentation technology

This section gives an overview of proposed instrumentation for technology for evaluation of seaweed farm pilot concepts and for future seaweed farms in operation.

5.3.1 Instrumentation technology for technology evaluation of sea farms

Equipment for measuring currents and waves is a basic requirement for the evaluation of sea farms, as described in Section 6.1.2. Further, to evaluate if the simulated hydrodynamic loads are reliable, the test rigs should be equipped with load sensors to allow monitoring loads in the main anchor lines. This may be used to compare the actual environmental loads with the actual load response, which then could be used for validation of the hydrodynamic models. Accelerometers and inclinometers may be used to further refine these analyses.

Wireless subsea sensor technology that could be used for this purpose are available, e.g. by the vendors Waterlinked (https://waterlinked.com/) or Thelma Biotel (https://www.thelmabiotel.com/). One of the main challenges is that capturing and transmission of data requires a surface module. It could be possible to integrate this into the mooring buoys. Another challenge is the lack of continuous power supply, as seaweed farms, in contrast to fish farms, do not have a feed barge in close vicinity that provides necessary infrastructure.

5.3.2 Instrumentation technology for operation of sea farms

The main advantage of being a seaweed farmer is that your plants requires very little care during the growth period. However, it is important to monitor the position of the seaweed farm to ensure that it is not displaced by the weather, by fishing gear or by other vessel traffic. A solution for this is to equip the farm with GPS-transmitters. This type of equipment was successfully installed at the two main mooring buoys for the test rig at Klovningen.

Once the period for harvesting is approaching it is useful to have a continuous monitoring of the status of the biomass. The seaweeds will normally be harvested at the time of maximum yield, but preferably before the fronds are degraded by microorganisms. Using personnel for monitoring and evaluating seaweed growth and quality is time consuming. ROVs (Remotely Operated Vehicles) or AUVs (Autonomous Underwater Vehicles) equipped with high quality cameras could be used for continuous or random monitoring of seaweed quality.

6 Design of test rigs at Klovningen and Orstranda

The abandonment of the pilot rig for further evaluation at sea necessitated design of an alternative test rig for technology evaluation. This test rig was also used for the cultivation tests in the Tareal 2 project. A test rig of similar design was developed for the inshore test site at Orstranda. The concept for the test rigs was selected based on the evaluation of alternative concepts described in Section 5.2.

6.1 Environmental conditions at test sites

6.1.1 Estimated maximum currents and waves at Klovningen

According to NS9415, design currents and design waves for the location should be established based on measurements. In lack of available measurements, the environmental conditions were estimated based on a numerical ocean model, SINMOD, developed by SINTEF Ocean (Slagstad and McClimans, 2005). The basis for estimating extreme currents and waves for 10- and 50-years return periods are included in Appendix D. The extreme currents and waves used in the analyses were:

Table 1: Estimated design waves and currents used in analyses (5m depth)

Return period	10-year	50-year
Wave height - Hs [m]	8.4	9.5
Current velocity [m/s]	0.57	0.61

6.1.2 Measured wave and current conditions at Klovningen

An Acoustic Wave and Current profiler (AWAC), Nortek signature (500kHz), was installed at the test site by the company Åkerblå (Åkerblå AS, 2020a, Åkerblå AS, 2020b). The AWAC was used for measuring current profiles and directional waves during the main growth period, from 03.03.20 - 10.06.20 (99 days).

The intention of the wave and current measurements was to be able to relate the measured environmental conditions to the measured forces on the cultivation rig, specifically the tension in the main mooring lines. Unfortunately, the project did not manage to raise funding for acquiring the required instrumentation for measuring forces and capturing time series of measured forces. The wave and current measurements are however useful for establishing environmental design conditions for the test site.

According to the wind measurements, maximum wind speed was 21.4 m/s from south-west, at the weather station Veiholmen, 40 km north-east of the wave measurement position (Åkerblå AS, 2020a). This means that no "extreme" weather conditions were captured during the measurement period. Stronger winds at such an exposed location would drive waves to higher values and could also increase the maximum currents.

The maximum measured currents were 54.9 cm/s at 5m depth and 47.5 cm/s at 12 m depth (Åkerblå AS, 2020b). The 10- and 50-years return periods are estimated based on the multiplication factors from NS9415:2009 (Table 2). The multiplication factors account for the relatively short measuring period and that extreme weather conditions could occur outside this measuring period.

Table **3** gives significantly higher design values than the calculated values (Table 1). The calculated values may seem underestimated, but the difference in results also underline the importance of having sufficiently long measurement periods, minimum one year according to NS9415, to reduce uncertainties and possibly over-conservative design values. It should also be noted that in extreme weather conditions, the wave forces are dominating and the contribution form currents to the total hydrodynamic loads are relatively small.

Table 2: Multiplication factors for return periods, based on one-month measurements (NS9415:2009)

Returperiode år	Multiplikasjonsfaktor
10	1,65
50	1,85

Table 3: Estimated design current based on current measurements (Åkerblå AS, 2020b)

Return period	10-year	50-year
Current velocity [m/s] – 5m	0.91	1.02
Current velocity [m/s] – 12m	0.78	0.88

The maximum measured wave height, H_{max}, during the measurement period was 3,7 m from south-west (Åkerblå AS, 2020a). Due to the relatively short duration of the wave measurements, it is not possible to extract long term statistics based on the wave measurements. However, the measurements show a fair correlation between high wind speeds and high waves, and a fair correlation between wind direction and wave direction for the highest waves at Klovningen. This information would be useful for any further prediction of wave conditions at this site.

6.1.3 Wave and current conditions at Orstranda

Wave and current conditions at Orstranda are based on design values used for the fish farm Or operated by Måsøval Fiskeoppdrett AS, which is located in close vicinity to the location Orstranda. The design values are based on the mooring analysis for this fish farms (Åkerblå AS, 2016), available through the Norwegian Coastal Administation's (Kystverkets) public journal system, eInnsyn.no.

Table 4: Estimated design waves and currents at Orstranda (Åkerblå AS, 2016)

Return period	10-year	50-year
Current velocity [m/s] – 5m	0.58	0.65
Wave height - Hs [m]	1.7	2.0

6.2 Soil conditions at test sites

6.2.1 Soil conditions at Klovningen

A seabed survey was performed by the company eSEA Marine, (eSEA Marine, 2019), including bathymetric mapping and seabed grab samples. The seabed grab samples showed that the seabed consisted of a top layer of fine sand, indicating suitable conditions for using plough anchors for the main anchor lines.

6.2.2 Soil conditions at Orstranda

No seabed survey was performed at Orstranda by the project nor was any information found through other sources. Since the soil conditions at Orstranda was unknown, it was decided to use clump weights as anchors at this location.

6.3 Environmental loads, load factors and load combinations

6.3.1 Wave height

The relationship between significant wave height, H_s, and maximum wave height, H_{max}, was set to $H_{max}/H_s = 1.9$, according to recognised design standards, see e.g. NS9415 (Norsk Standard, 2009) or DNV-RP-C205 (DNV GL, 2010).

6.3.2 Wave period

The most probable individual wave period T_{Hmax} to be used in conjunction with a long term extreme wave height H_{max} was taken according to DNV-RP-C205 (DNV GL, 2010), giving:

$$T_{H\max} = 2.94 \cdot \sqrt{H_{\max}}$$

6.3.3 Load factors

Load factor for dynamic loads was taken according to NS9415 (Norsk Standard, 2009):

Table 5: Load factors for anchor lines, NS9415

Type analyse	Lastfaktor
Statisk analyse	1,6
Kvasistatisk analyse	1,15×DAF[1)]
Dynamisk analyse	1,15
Ulykkesgrense (brudd i fortøyningsline)	1,0
Springflo	1,0
[1)] Her brukes en faktor på 1,15 multiplisert med dynamisk amplifikasjonsfaktor (DAF). Dynamisk amplifikasjonsfaktor ≥1,1. Valg av verdi på DAF skal begrunnes og dokumenteres.	

6.3.4 Load combinations

Load combinations for simultaneously acting current and waves was applied according to NS9415:2009 (Norsk Standard, 2009).

Table 6: Load combinations for simultaneously acting current and waves, NS9415

Kombinasjoner	Returperiode, miljølast år		
	Strøm	Vind	Bølge
1	50	10	10
2	10	50	50

6.4 Load effects and simulation of loads in FhSim

The forces on the cultivation ropes are calculated based on drag tests performed by SINTEF Ocean (Endresen et al., 2019). The towing direction in the tests was perpendicular to the ropes, giving forces as indicated in Figure 20, for ropes with moderate growth (3-5 kg/m) and current speeds up to 0,8 m/s. The loads on each cultivation rope, applied in the model, was found using a conservative curve fitting for the upper bound values.

This model is assumed to give conservative estimates for drag forces acting on single cultivation ropes. In seaweed farms consisting of horizontal cultivation ropes, the ropes are typically placed less than two meters apart from each other. This means that, in the case of currents acting perpendicular to the ropes, there will most likely be hydrodynamic shadow effects between the ropes that reduces the total hydrodynamic forces, similar to the concept of drafting/slipstreaming in cycling. It is not possible to give any scientific estimate for this force reduction unless further CFD (Computational Fluid Dynamics) calculations or model tests are performed. Hence, no reduction factor for hydrodynamic shadow effects was applied in the calculations, although this effect may be significant. Typical extreme values for currents in this area are in the range of 0,5-1,0 m/s.

In addition to the current forces, the waves are also causing water particle motion that causes drag loads on the cultivation ropes. The water particle velocity decreases exponentially with depth. E.g. in H_s =2.0, the water particle velocity is 2,4 m/s at the surface, 1,7 m/s at 2m depth and 1,2 m at 4 m depth. This means that for seaweed farms in exposed areas, with cultivation ropes just beneath the sea surface, the drag forces from the waves will normally be dimensioning.

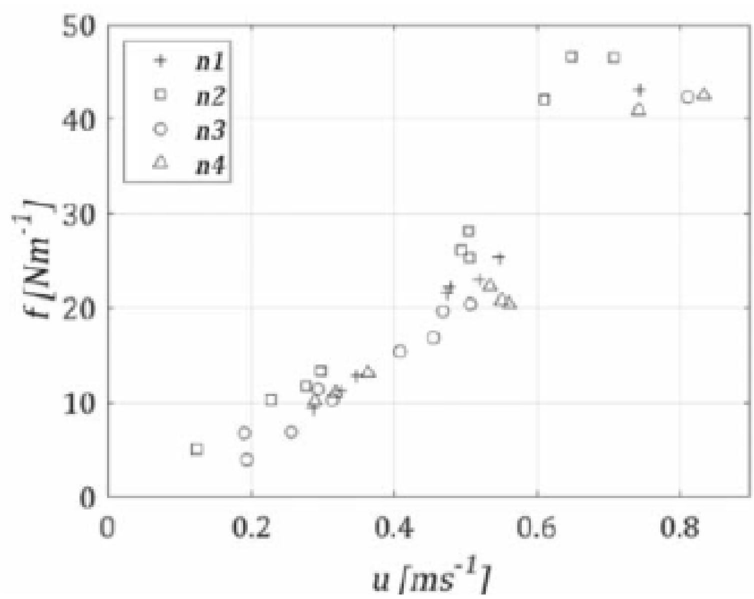

Figure 20: Average drag force per meter for all kelp ropes as a function of towing velocity (Endresen et al., 2019)

6.5 Simulated characteristic extreme forces

Wave loads and drag forces on the test rig were calculated based on regular waves. Wave forces and currents acting perpendicular to the cultivation ropes give the governing load cases. Details of the analyses performed by the simulation programme FhSim are included in Appendix E. The simulated maximum characteristic loads are given in Table 7 and Table 8.

Table 7: Simulated maximum characteristic loads from FhSim - Klovningen

Component	Simulated extreme forces [kN]
Anchor lines	48
Grid lines/load carrying ropes	48
Buoy line	27
Cultivation ropes	9

Table 8: Simulated maximum characteristic loads from FhSim - Orstranda

Component	Simulated extreme forces [kN]
Anchor lines	10
Grid lines/load carrying ropes	8
Buoy line	7
Cultivation ropes	2,5

6.6 Structural design of test rigs

Based on the estimated maximum characteristic design loads, dimensioning of the structural components was performed according to NS9415, by applying appropriate load factors as given in Table 9. Details included in Appendix F.

Table 9: Material factors for anchor lines, NS9415

Type	Materialfaktor
Syntetisk tau	3,0
Syntetisk tau med knute	5,0
Kjetting og kjettingkomponenter	2,0
Brukt kjetting	5,0
Koblingsplater og andre koblingspunkter av stål*	1.5
Sjakler	2,0
Fjellbolter og andre bunnfester	3,0
* Første flyt	

7 Evaluation of project results and discussion on future directions

7.1 Identification of relevant seaweed farm concepts for exposed areas

Seaweed farms for scaled seaweed cultivation does not exist in Norway. The existing Norwegian seaweed farms are small scale and requires a lot of manual work operations, which will not be cost-efficient for large scale production. There is a potential for scaling up the existing seaweed farm concepts in Norway if a cost-efficient and robust method for connecting and disconnecting the cultivation ropes to the mooring grids is developed.

The existing Norwegian seaweed farms are placed in sheltered waters. The semi-rigid arrangement of these seaweed farm concepts, with tensioned cultivation ropes in the most wave affected zone, makes these concepts unsuitable at more exposed locations. The cultivation rig used by Ocean Rainforest, with vertical cultivation ropes, has been demonstrated for rough weather conditions. One of the advantages with this concept is that the rig partly enters into a "survival mode" in rough weather conditions, by allowing the smaller buoys attached to each cultivation rope to submerge due to the tension in the cultivation ropes. This effect reduces the total hydrodynamic loads, which means the seaweed farms could be designed with fewer and smaller anchors and reduced rope dimensions compared to seaweed farm concepts with horizontal ropes.

It should be further investigated how this concept could be used for scaled seaweed production and how to mechanize harvesting process. Alternative concepts for weather exposed locations should also be further investigated.

7.2 Evaluation of test rig design, installation and operation

A concept with vertical cultivation ropes, similar to the Macroalgal Cultivation Rig (MACR) designed by Ocean Rainforest was used for evaluation and testing at Klovningen site. The available length/area for the cultivation ropes was relatively short since the anchor lines also needed to be placed inside the granted cultivation area. The horizontal rope at 10 m depth, supporting the vertical cultivation ropes was only 60 m long, see sketches in Appendix G. This arrangement resulted in a relatively stiff mooring system, meaning that when inspection of the cultivation lines was needed and/or when harvesting from the cultivation lines, a large crane (from e.g. a service vessel) was needed to lift the horizontal rope to the surface. For a full-scale seaweed farm using this concept, the horizontal rope could be significantly longer, giving reduced geometrical stiffness and ease recovery of the cultivation lines to the surface.

All components in the test rig are also subject to wear and tear due to the dynamics from the waves. This needs to be thoroughly considered in design and construction of the seaweed farms. The project experienced loss of a mooring buoy, causing partial temporary breakdown of the rig and permanent loss of a cultivation rope. The reason for the lost mooring buoy was most likely an improperly secured thimble and/or wrong type of thimble used, causing wear of the rope between the subsurface connection ring and the mooring buoy. The reason for the lost cultivation rope has not been identified, but it is likely due to wear in the connection between the cultivation rope and the main load carrying rope. ROV surveys conducted at 21st of March and 23rd of April showed no other visual signs of damage to the test rig during the test period.

The maximum measured wave height, H_{max}, during the test period was 3,7 m from south-west (Åkerblå AS, 2020a) and the maximum measured currents were 54.9 cm/s at 5m depth and 47.5 cm/s at 12 m depth (Åkerblå AS, 2020b).

7.3 Identification of technological challenges and improvement needs

7.3.1 Estimation of loads and use of safety factors in design

Anchors, mooring lines and other structural components constitute a significant share of the total construction cost for a seaweed farm. Uncertainties in theoretical models are normally handled by adding conservative safety factors. When safety factors are added to the environmental loads, to the load effects and finally in the structural design, the result could be that the final design is over-dimensioned, giving unnecessary high costs. By further developing the hydrodynamic models for seaweeds cultivated on ropes or other substrates, better and more reliable estimates that reduce conservatism and contribute to more cost-efficient design could be achieved. Also, as mentioned in Section 3.1, a future design standard for seaweed farms should consider reduced load- and material factors to reflect a reasonable safety level.

7.3.2 Equipment for real time monitoring of mooring line loads

Wireless subsea load sensor technology is available. One of the main challenges is that transmission of data requires a surface module. It could be possible to integrate this hardware into the mooring buoys together with battery power supply. This should be further investigated.

7.3.3 Future offshore seaweed farms – technical and functional requirements

Large scale offshore cultivation of seaweeds requires large seaweed farms and it is likely that these farms will be located at exposed weather locations. The following factors are considered important for development of future offshore seaweed farms in Norway:

Cost-efficiency
The seaweed farm concepts should be designed based on a holistic approach considering all phases of the cultivation process, including construction, seeding, operation, monitoring, maintenance and de-commissioning. Design of future seaweed farms should facilitate a high degree automation which makes seaweed farming cost-efficient.

Exposed locations
Seaweed farms at exposed locations give improved cultivation yield compared to inshore and near shore locations (Broch et al., 2019). Cultivation at exposed locations may also reduce area conflicts. Increased knowledge on hydrodynamic forces and interactions and technology development are considered essential for robust and cost-efficient design of seaweed farms.

Monitoring
Methods for real time monitoring of both biological conditions and structural integrity of seaweed farms is essential for continuous monitoring and reduced need for personnel.

Safety
Robust seaweed farms that reduces the risk for loss of structural components and thereby reduces risk for marine traffic. Handling and operation procedures for seaweed cultivation and harvesting must consider safety of personnel.

Environmental sustainability
Use of eco-friendly materials that minimize environmental impact, e.g. by using ropes of natural and/or biodegradable material.

7.4 Spin-off effects to other local business activities – by Vindel

To achieve efficiency and economy of scale for commercial cultivation of seaweed at Nordmøre, it was necessary to engage relevant local companies with a passion for developing new technology for seaweed cultivation in order to build local competence, skills and commitment.

There are significant business opportunities in the region for developing a sustainable seaweed industry, both for companies who focus on cultivation, for processing industry and especially for suppliers of technology, logistics and services. Algea, one of the oldest seaweed companies, is also located in Kristiansund. For over 80 years the company has been harvesting and processing *Ascophyllum nodosum* for use in agriculture and animal feed. In 2002 the company joined the Italian Valagro Group.

In October 2019 Vindel AS arranged a workshop with around 30 local companies to discuss challenges and opportunities within seaweed cultivation technology and services.

There are currently two commercial businesses in the region with cultivation locations:

- Algevekst AS is a newly established commercial business with four cultivation licenses in the region (located in Aure, Nordmøre).
- Laminiara AS has six cultivate licenses (located in Kristiansund, Nordmøre).

In the project we have used mainly two service providers: Esea Marine AS and Abyss Aqua AS. Their tasks included mapping the area, handling the cultivation rig, surveillance, and other services. OceanFront AS was requested to handle and coordinate the operations. Åkerblå AS, with expertise within oceanography, delivered a wave and current report for the cultivation location.

There are several exiting innovative companies in the region. Greenshore AS and Norsk Frysetørking AS are exploring new ways to extract moisture from raw materials as seaweed. Storm Marine AS delivers new harvesting technology, MacGregor AS offers new crane technology and Møre Maritime AS contributes with a specialized harvesting vessel concept. Satpos AS developed a modified positioning system on the mooring buoy delivered by Certex AS.

It was important to engage local research companies and vocational school. Students specializing in process technology were offered the opportunity to participate in workshops and trips to the cultivation location. The local higher vocational school in Kristiansund has a long tradition with process technology and has invested in a micro- and macroalgae processing laboratory. Students from the local vocational school specializing in aquaculture have also been participating in monitoring surveys at the seaweed farming sites. Young and Unemployed Digital Talents from all over the county were engaged to create a 3D-version and simulation of the ProAqua rig on the location. The results can be found on YouTube; https://www.youtube.com/watch?v=Tm5h0DVosaY

Another important effect is that the development of seaweed farming also substantiates local interest and growth in businesses looking at other marine resources, such as Tunicate, Sea cucumber, Sea urchin and Bottarga production.

7.5 Continued development and funding of test site – by Vindel

We need to set up a complete value chain to scale up and industrialize the seaweed industry, and it takes time to build a new industry. One way of doing this is to establish an Ocean Seaweed Centre to facilitate a multidisciplinary partnership between the county municipality, other stakeholders, local companies and the newly planned Campus for higher education and research institutions.

In order to develop new business areas, Møre og Romsdal County Municipality will strengthen its work within development of industrial cultivation of macroalgae. They will facilitate the establishment of test fields for the cultivation of various species of macroalgae in a protected and exposed environment and has recommended an additional NOK 2 million investment in 2020 in the project they have named Ocean Seaweed Centre. Based on experience from the Akvalab and Tareal projects, we want to explore the possibilities to go further offshore to maximize the biological growth potential of seaweed and at the same time minimize conflicts with e.g. shipping traffic, fishery, salmon farming and other interests. A promising use of cultivated seaweed is to capture CO_2. This will require large cultivation areas to make a climate impact. Some rough estimates indicate nevertheless that it can be cost efficient compared to other alternatives with the same impact.

Going forward, the county has ordered a research project to evaluate potential technologies for processing of macroalgae. Møreforsking AS, the local research institute with expertise within marine raw materials, will conduct this research to find the most feasible processing technology to set up in a testing facility. One of the key challenges for the industry is to maintain high quality after harvest, as large amounts of biomass will be harvested within a limited period (approx. 4-6 weeks). A market research must also be conducted to find the right market segments and compile this with the best processing pathway for the seaweed.

Innovative and existing technologies can be transferred from other industries with some modifications. The most promising concepts include:

- Sensors for monitoring environmental conditions, seaweed growth and integrity of seaweed farms.
- Real time camera surveillance using ROV/AUV.
- New or modified vessels with mechanized and automated harvesting tools.
- Process technologies to create different products (testing other seaweed species and mix with other marine raw materials).

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ÅKERBLÅ AS 2016. Fortøyningsanalyse for Or

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ÅKERBLÅ AS 2020b. Strømrapport - Måling av strøm på 5m og 12m på Griptaren i mars - juni 2020.

Appendices

A : Evaluation of pilot rig from Proaqua

Detaljer

Bøyer

4 gule bøyer

Dimensjoner [m]	1.17x1.17m
Høyde [m]	0.6
Vekt [kg]	85
Oppdrift [kg]	500

2 oransje bøyer

Radius [m]	0.32
Høyde [m]	0.97
Vekt [kg]	19
Oppdrift [kg]	230

Fortøyning/tauverk

Lengde fortøyning [m]	40	(ifra de 4 bøyene og ned til svivel)
Lengde svivel/anker [m]	8	(ifra svivel ned til bunn/anker)
Diameter [m]	0.024	
Vekt pr. fortøyning [kg]	180	(samlet vekt 4x180 kg)
Stivhet [GPa]	2	

Ring

Diameter [m]	24	
Vekt pr. lengde [kg/m]	20.6	(dette tilsvarer nøytral vekt i vann)
Rørdiameter [m]	0.16	
Ønsket dybde [m]	10	(evt. posisjon avhenger av strømmen som kan dra ringen opp og ned)

Svivel

Vekt [kg]	200	
Oppdrift [kg]	300	(bøye)

Tare og dyrkningsmatte

Maksimal vekt [kg]	1500	(totalt, tare + dyrkningsmatte)
Lengde på tau med tare [m]	150	(samlet lengde, antatt 2 m avstand mellom tauene)

Konfigurasjon

Bunn dybde [m]	38	
Ønsket dybde på ringen [m]	10	(evt. posisjon avhenger av strømmen som kan dra ringen opp og ned)

Miljøtilstander i simuleringene

Tilstand 1

Strøm, Vc [m/s]	0.6

Tilstand 2

Strøm, Vc [m/s]	0.6
Bølge, Hs [m]	2
Bølge, Tp [s]	4

Gjennomsnitt dragkraft på tare

Tilstand 1, kraft [N]	11500	(kun strøm)
Tilstand 2, kraft [N]	25500	(strøm + bølger, ringen ligger på ca. 10 m dyp)

Håndberegninger av dragkrefter på tare oppsummeres i Vedlegg.

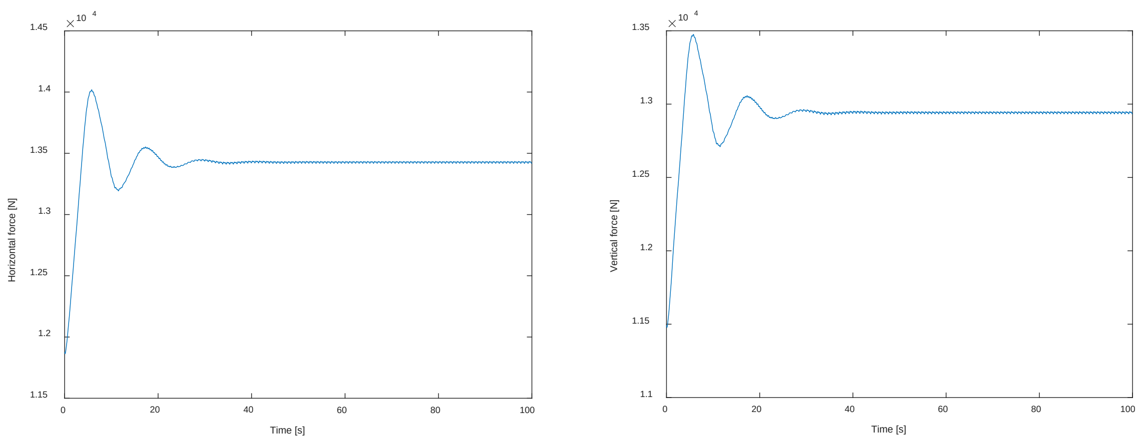
Resultater fra simuleringene

Tilstand 1 (kun strøm)

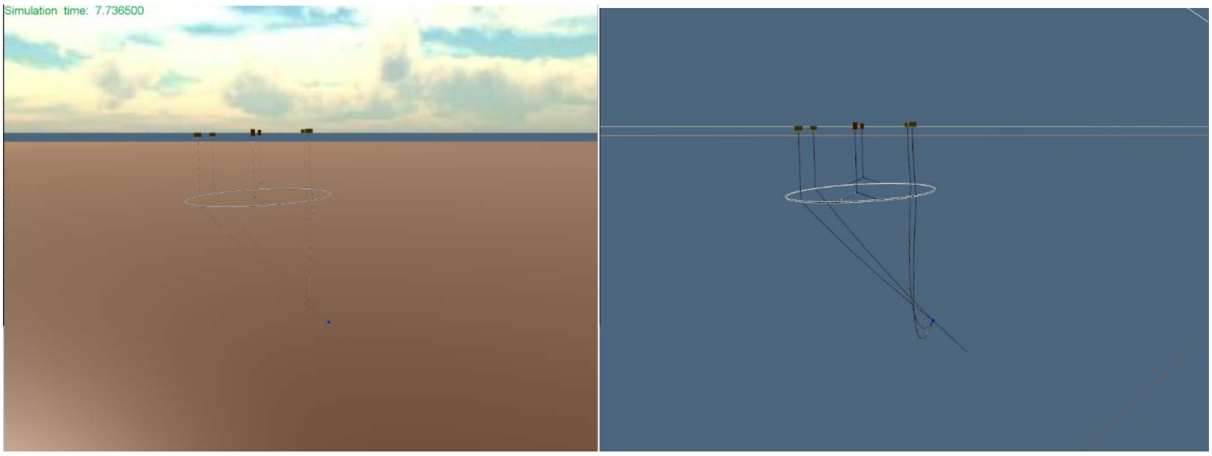
Simuleringen viser at med 180 kg på hver fortøyning kan anlegget ha tilstrekkelig horisontalstivhet for å motvirke strøm på 0.6 m/s når det er maks 1.5 tonn tare på ringen. For å sikre at ringen ikke blir dratt opp og ligger i horisontal posisjon, anbefales det at den må ha minst 50-100 kg vekt i vann.

Bøyene på nedstrøms side må ha minst 1.5 tonn samlet oppdrift (750 kg netto oppdrift per bøye), ellers kan alle bøyene blir dratt betydelig ned under vann når fortøyningene er strammet av ringen pga. strøm. Bøyene på oppstrøms side har lite å gjøre med horisontale krefter på ringen.

I en statisk tilstand blir ankerkreftene ca. 1.4 tonn i både horisontal og vertikal retning.



Krefter på anker

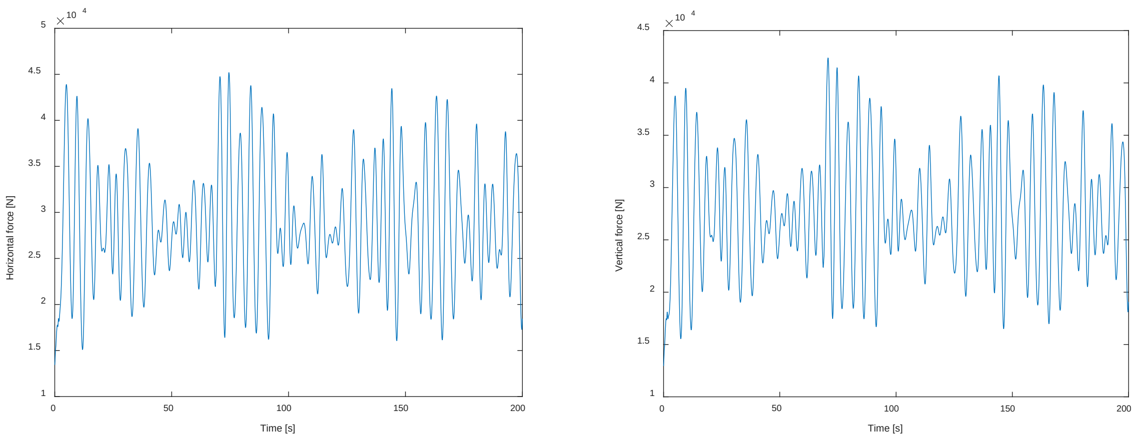


Diverse bilder av anlegget (Tilstand 1: Vc = 0.6 m/s, ingen bølger)

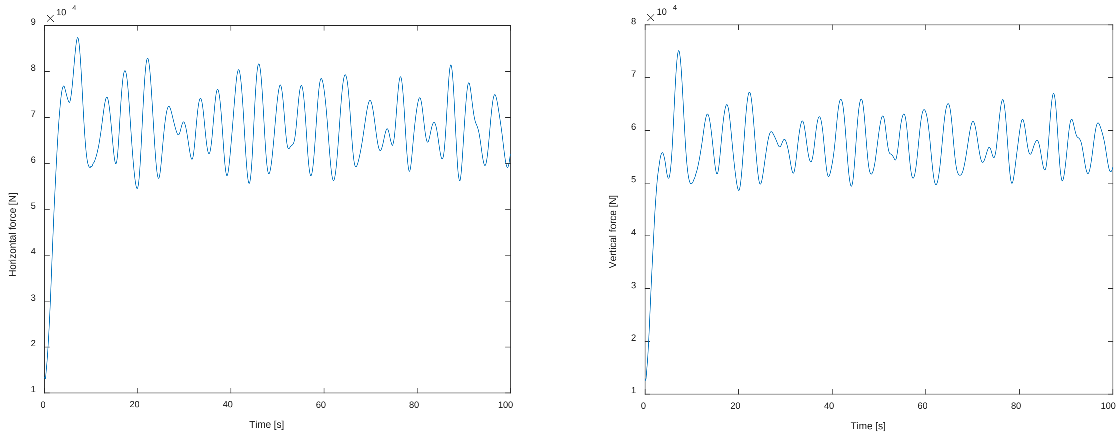
Tilstand 2 (strøm og bølger)

Selv om ringen ligger på 10 m dyp, kan det være betydelig større dragkrefter på tare og selve ringen når det er bølger på ca. 2 m (T = 4 s), i tillegg til strømmen (Vc = 0.6 m/s). Hvis ringen er nøytral i sjøen, er det ingenting som kan holde den horisontalt på 10 m dyp. I denne situasjoner er det stor risiko at ringen blir dratt opp mot overflaten hvor bølgeeffekten er enda større.

Tidsseriene nedenfor viser ankerkrefter for både 2m og 10 m dyp på ringen. Hvis man klarer å sikre ringen på 10 m dyp (ved f.eks. ekstra vekt) da blir maks ankerkreftene i både horisontal og vertikal retning ca. 4.5 tonn. Hvis ringen kommer delvis på overflaten, kan ankerkreftene bli ca. 9 tonn både horisontalt og vertikalt.



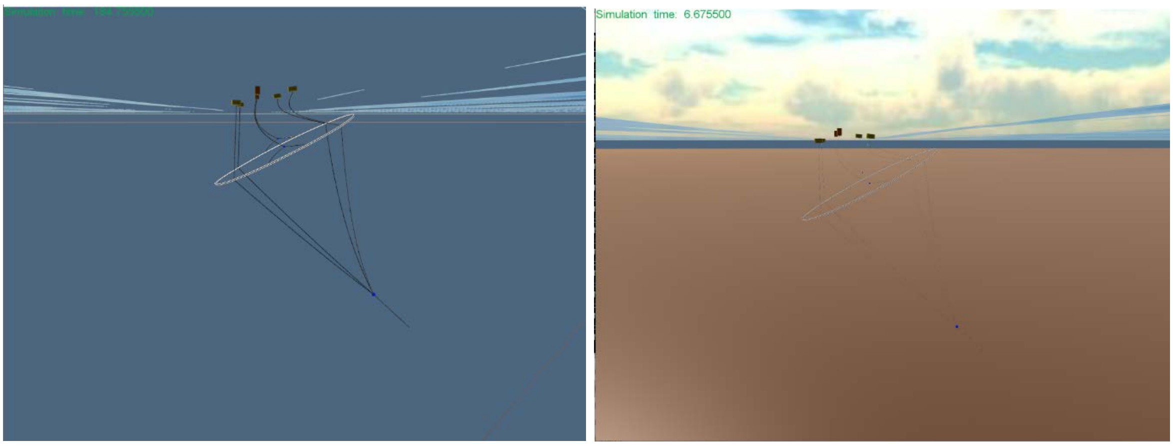
Krefter på anker når ringen ligger på 10 m dyp



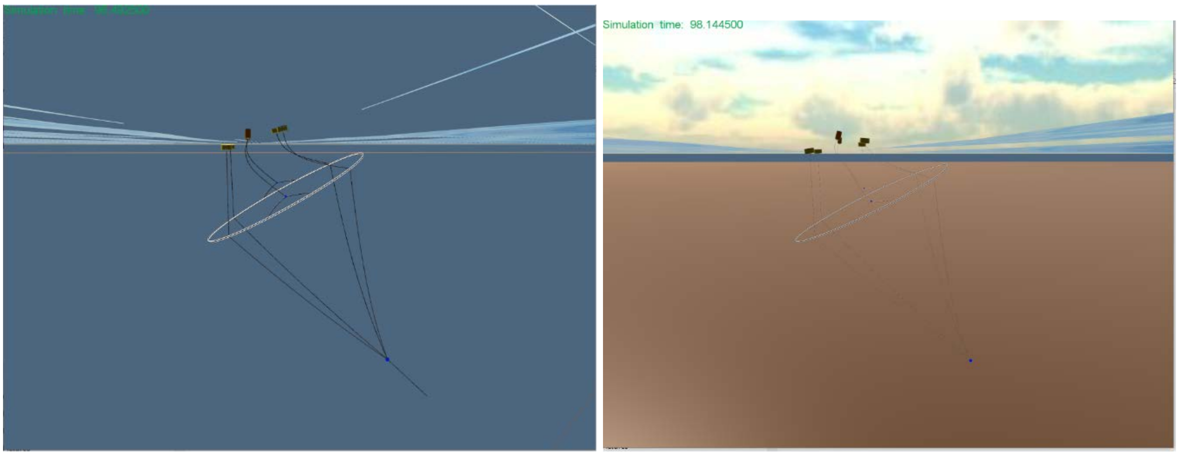
Krefter på anker når ringen ligger på 2 m dyp

Ring med ekstra vekt

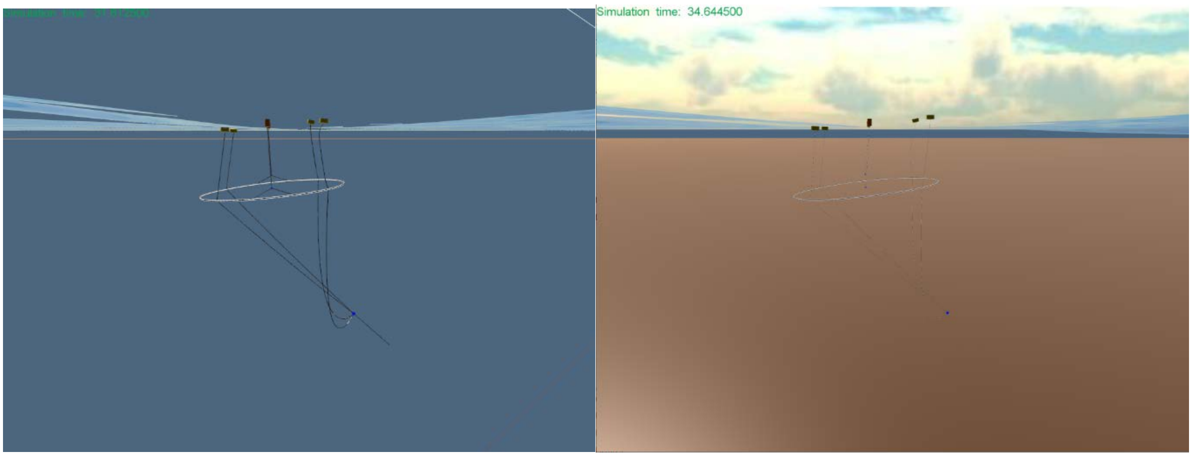
Det ble forsøkt "å rette" ringen når den ligger skjevt pga. bølger og strøm (Tilstand 2) ved å legge ekstra vekt på den. Bildene nedenfor viser at ringen må ha minst 500 kg ekstra vekt for at den kan balansere seg selv og motvirke store vertikale bevegelser.



Ring med nøytral vekt i vann



Ring med 100 kg vekt i vann



Ring med 500 kg vekt i vann

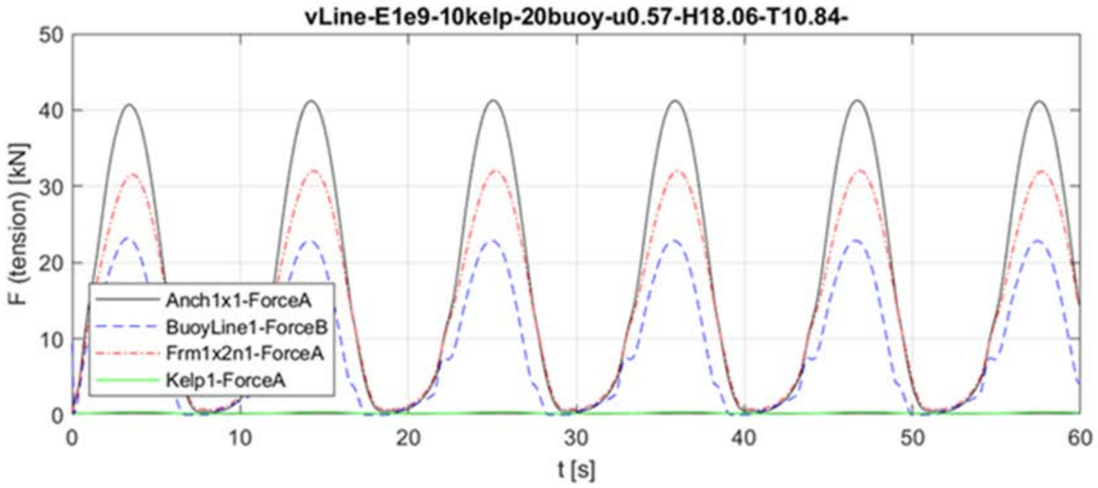
Konklusjon

Større bøyer og tyngre fortøyninger (se avsnitt Detaljer) kan holde anlegget i en akseptabel tilstand i en strøm på 0.6 m/s med forbehold at det er maks 1.5 tonn tare på dyrkningsmatte (tilsvarende 150 m tau med maks 10 kg tare pr meter lengde), og ringen er sikret mot tilt ved f.eks. 50-100 kg ekstra vekt på. Ankerkreftene blir ca. 1.4 tonn i både horisontal og vertikal retning.

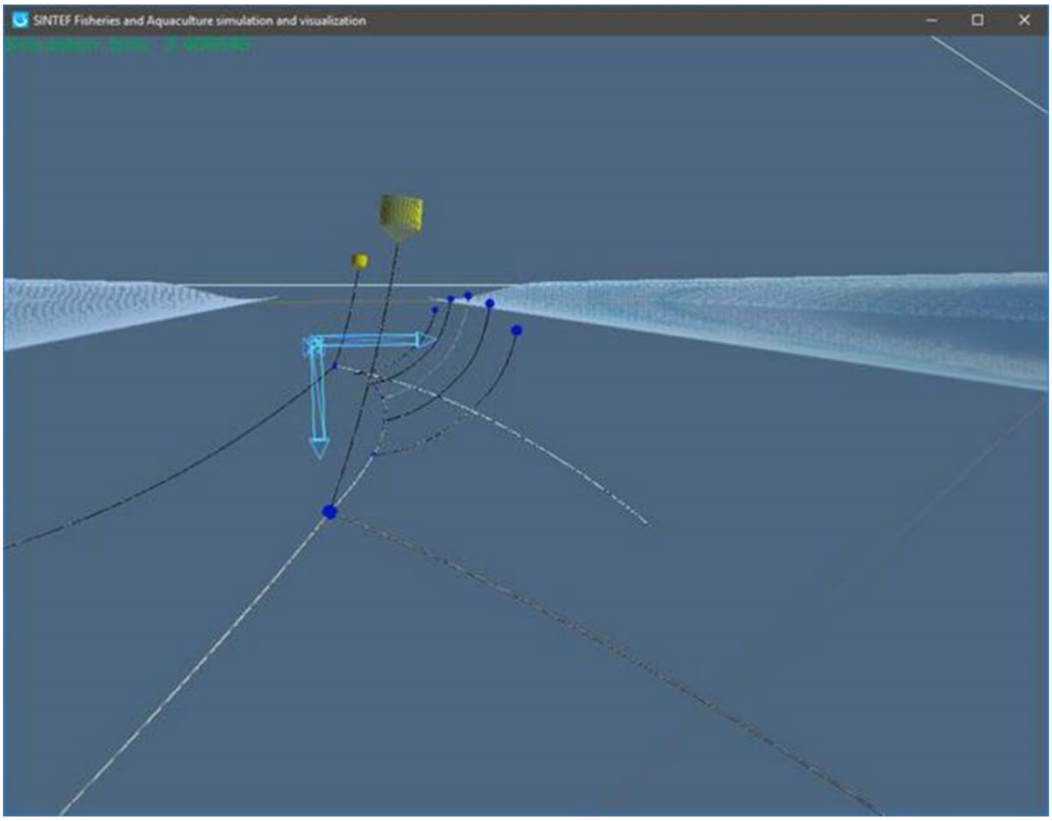
Anlegget virker ustabilt i bølger. Selv om ringen ligger på 10 m dyp i strøm på opp til 0.6 m/s, blir den dratt opp når bølger kommer i tillegg. For å sikre at ringen forblir på ønsket dybde, må den ha minst 500 kg vekt i vann. I tillegg må bøyene på nedstrøms side ha samlet oppdrift på 2.5 tonn (1,25 tonn per bøye), og anker må klare å holde 4.5 tonn i både horisontal og vertikal retning.

B : Evaluation of alternative concepts

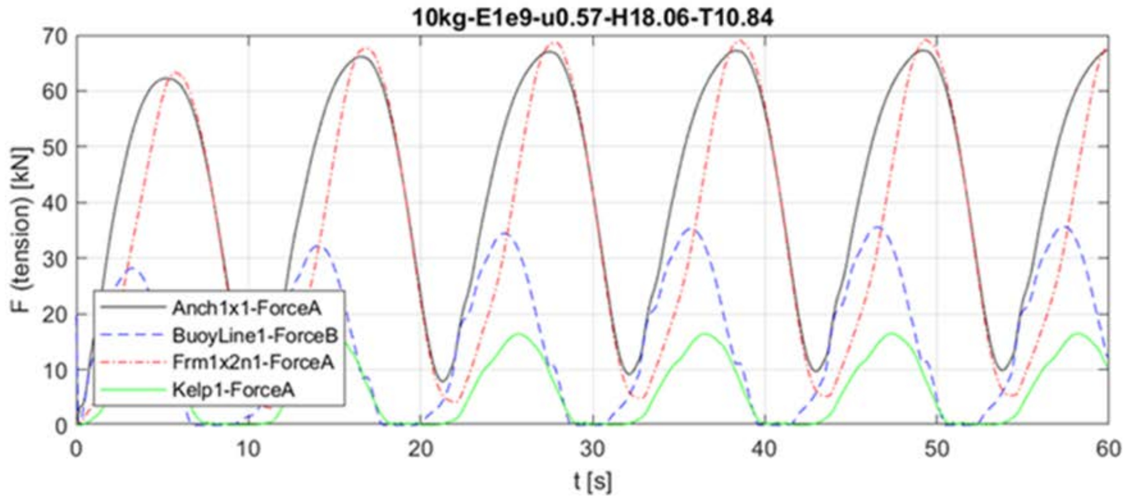
Results from simulation of vLine-concept:



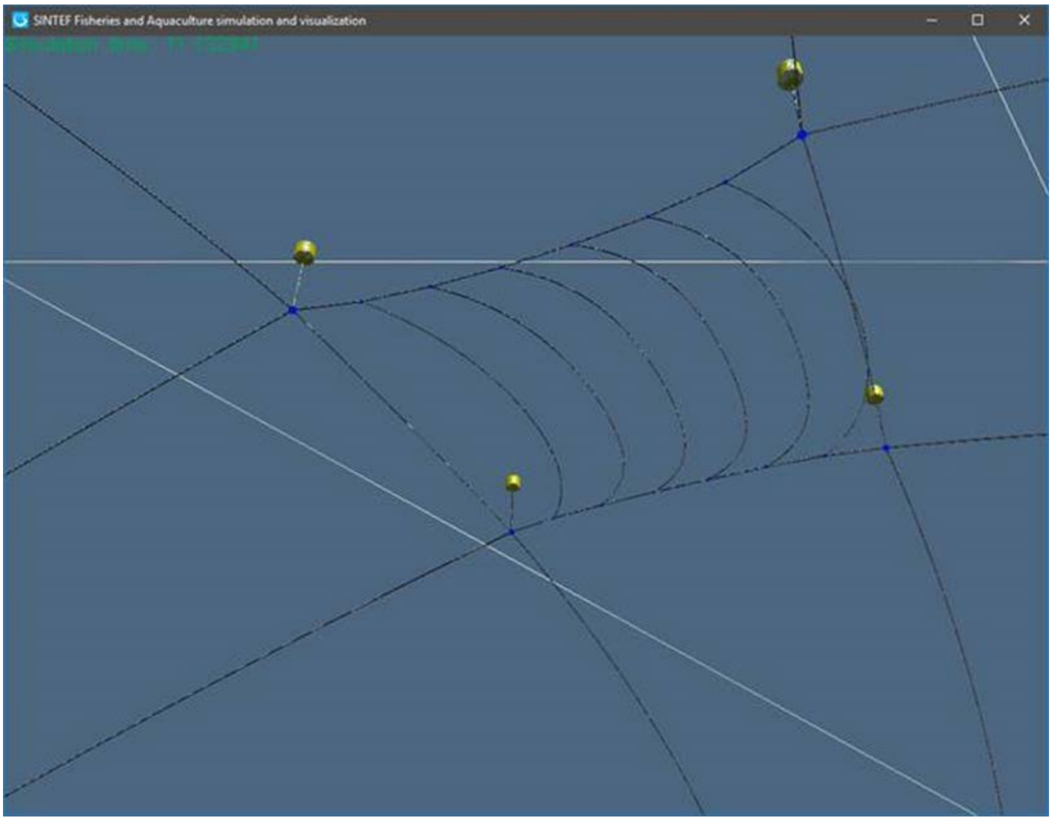
Visualisation of vLine-concept in extreme wave condition:



Results from simulation of hLine-concept:



Visualisation of hLine-concept in extreme wave condition:



SINTEF

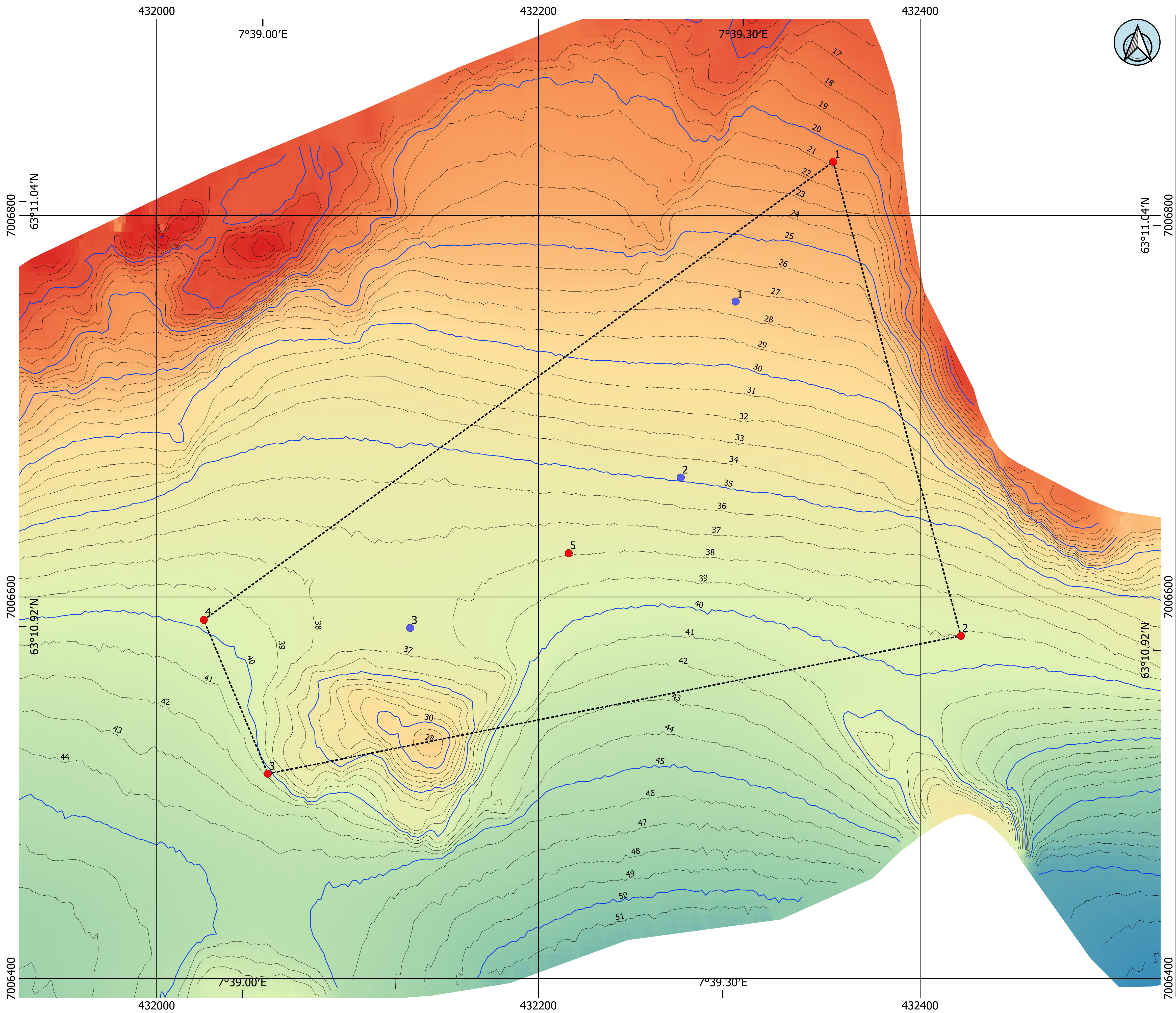
C : Field layout Klovningen – bathymetric map provided by eSea Marine

eSEA MARINE

Klovningen: Dybder i sjøkart null - målt juni 2019

www.eseamarine.no

INNOVATIV. FLEKSIBEL. FRAMTIDSRETTET.



Tegnforklaring

Kontur 1m

Kontur 5m

Punkt anlegg

1 - 63°11,056' N 7°39,358' Ø

2 - 63°10,923' N 7°39,444' Ø

3 - 63°10,880' N 7°39,013' Ø

4 - 63°10,923' N 7°39,971' Ø

5 - 63°10,944' N 7°39,198' Ø

Farger

-60

-50

-40

-30

-20

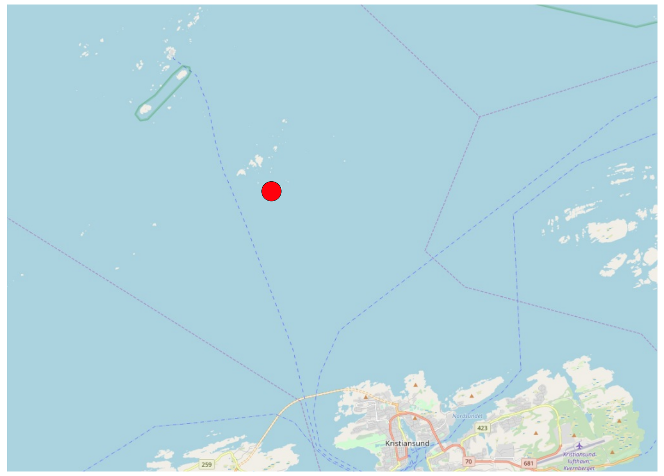
-10

Bunnprøver

1 - 63°11,016' N 7°39,299' Ø

2 - 63°10,966' N 7°39,267' Ø

3 - 63°10,922' N 7°39,100' Ø



0 25 50 75 100 m

VINDEL

Kartdato 24.06.19

EUREF89 / ETRS89

Papirstørrelse A3

D : Estimated extreme currents and waves at Klovningen

Contents

List of Tables and Figures

General

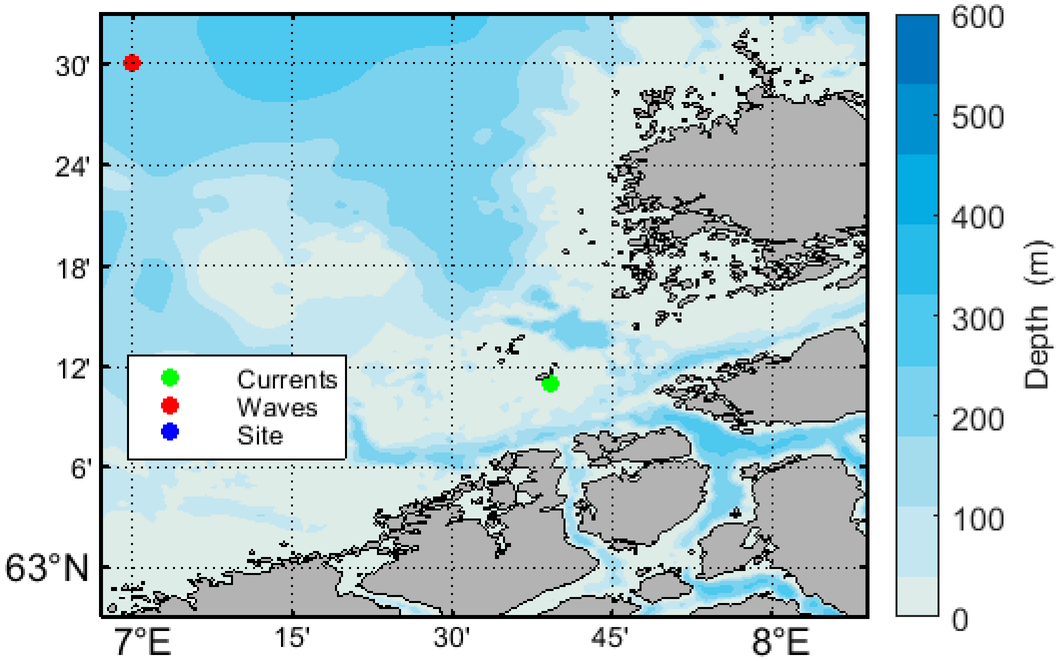


Figure 1 Map of the area

In Figure 1, the location of the site is depicted (blue circle; partially overlapping with the current circle), as well as the data analyzed. Wave data (red circle) comes from the newly released ERA5 global dataset (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5) and covers a 39- year long period (1979-2017) with 1-hourly data. Current data (green circle) comes from SINMOD run, refers to Depth=5m, and covers the period 2016.03.01–2017.01.23.

Waves

Extreme-value analysis for the wave location depicted in Figure 1 has been performed, using the Method of moments for return periods 10:10:100 years. The corresponding return wave height is given in Table 1, and plotted in Figure 2.

Table 1 Return values of significant wave height

Return period (years)	Return Hs (m)
10	12.03
20	12.71
30	13.09
40	13.36
50	13.58
60	13.75
70	13.90
80	14.02
90	14.13
100	14.23

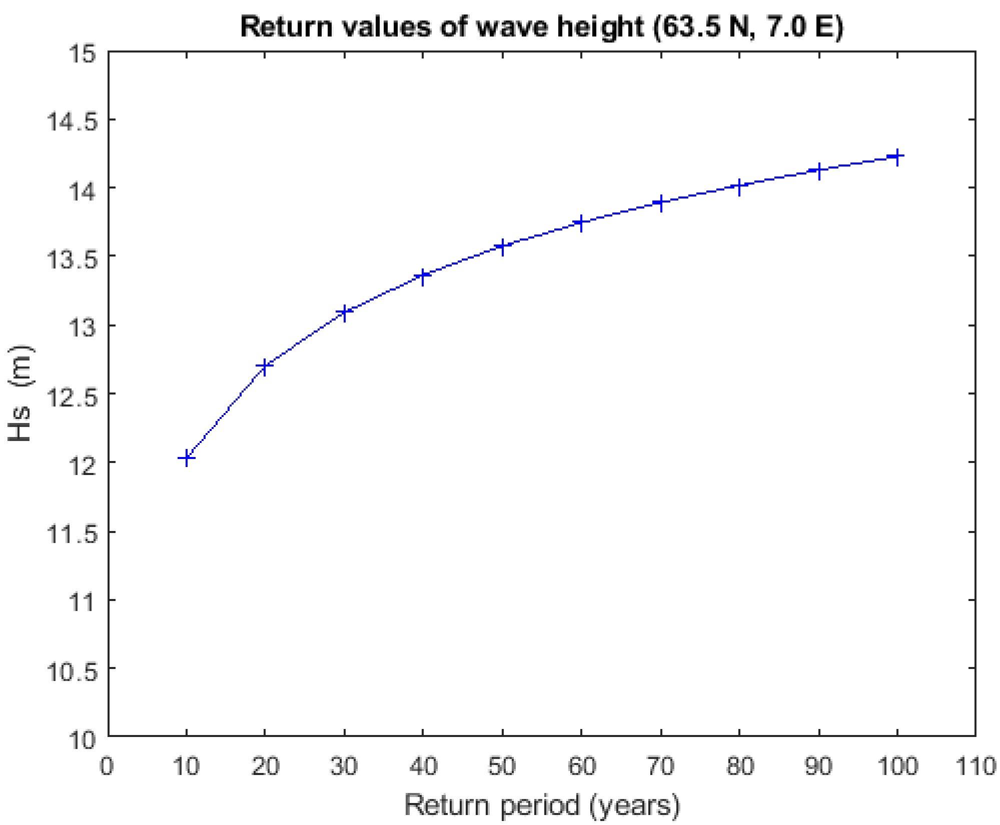


Figure 2 Return values of significant wave height

Currents

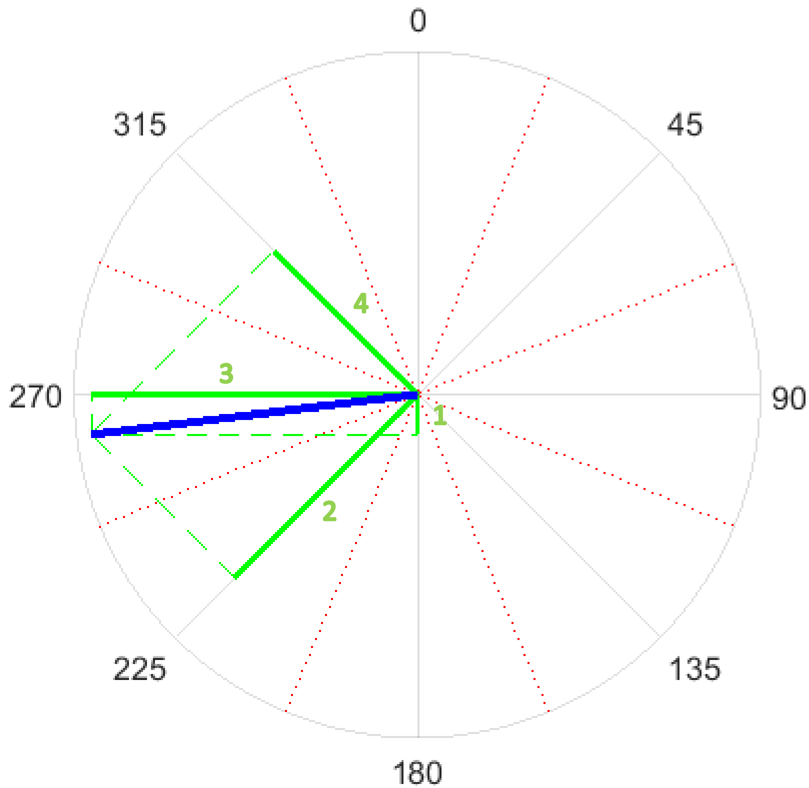


Figure 3 Projection of an arbitrary current vector (blue line) to all the neighboring sectors (green lines)

Before the analysis, all current vectors have been projected to the centerline of each directional sector (i.e., 0, 45, 90, 135, 180, 225, 270, 315 deg). In this way, their contribution is taken into account (proportionally) not only to the dir. sector where they belong to, but also the neighboring sectors.

In Figure 3, an example is given with an arbitrary current vector (blue line) is heading towards a direction of ~263 deg. According to the traditional analysis, this vector belongs to the directional sector [247.5 292.5]. However, by projecting it to the centerlines of all sectors, we clearly see that that there is a contribution also from the neighboring sectors (green lines 1-4): [157.5 202.5], [202.5 247.5], [247.5 292.5], [292.5 337.5]. A side effect is that the contribution to its own sector (in the present example [247.5 292.5]) is slightly decreased.

Table 2 Return values of current speed (depth=5m)

Return period (years)	Return v (m/s)
0.04	0.37
0.2	0.44
1	0.50
10	0.57
25	0.59
50	0.61
75	0.62
100	0.63

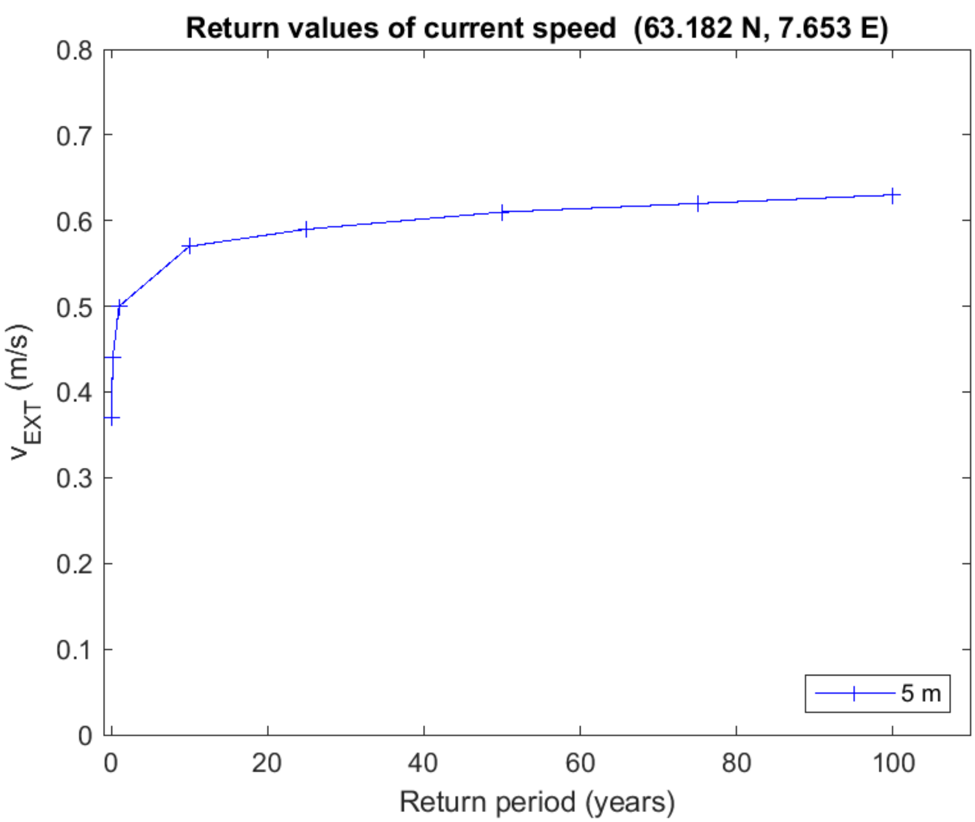


Figure 4 Return values of current speed (depth=5m)

NOTE. These extreme-value predictions seem to be a bit low and they should be used with caution. Probable reason is that current data cover a short period of less than one year (2016.03.01-2017.01.22).

Table 3 Maximum current speed per directional sector

Direction (deg)	Max current speed (m/s)
0	0.2221
45	0.4958
90	0.5261
135	0.2491
180	0.2185
225	0.3514
270	0.4058
315	0.2649

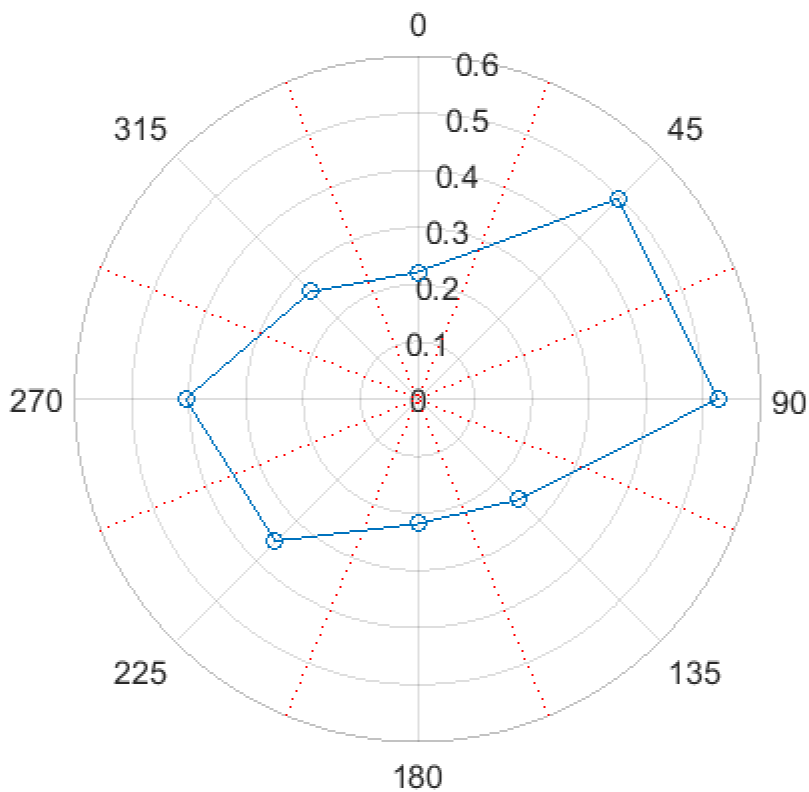
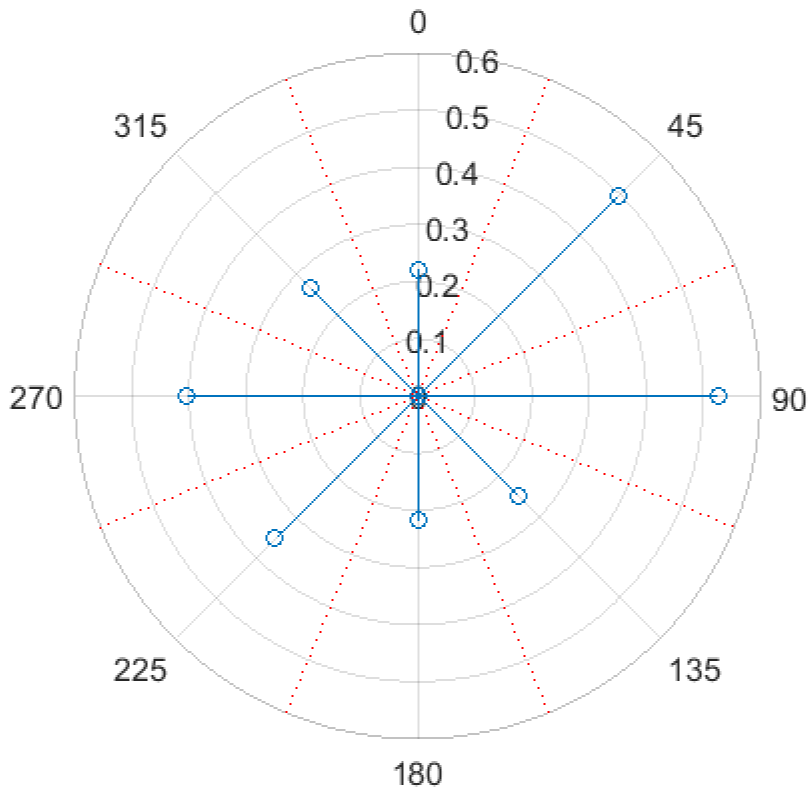


Figure 5 Maximum current speed per directional sector



Alternative for Figure 5

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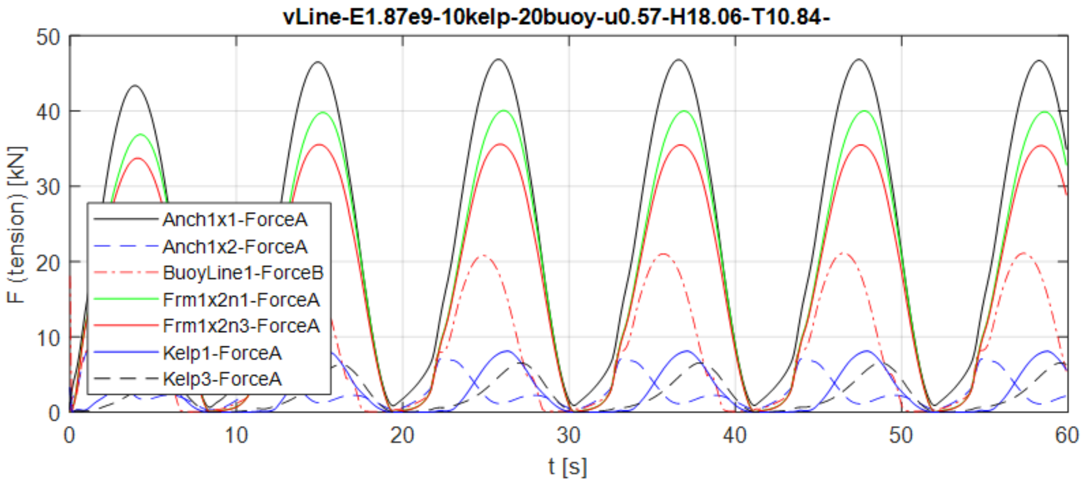
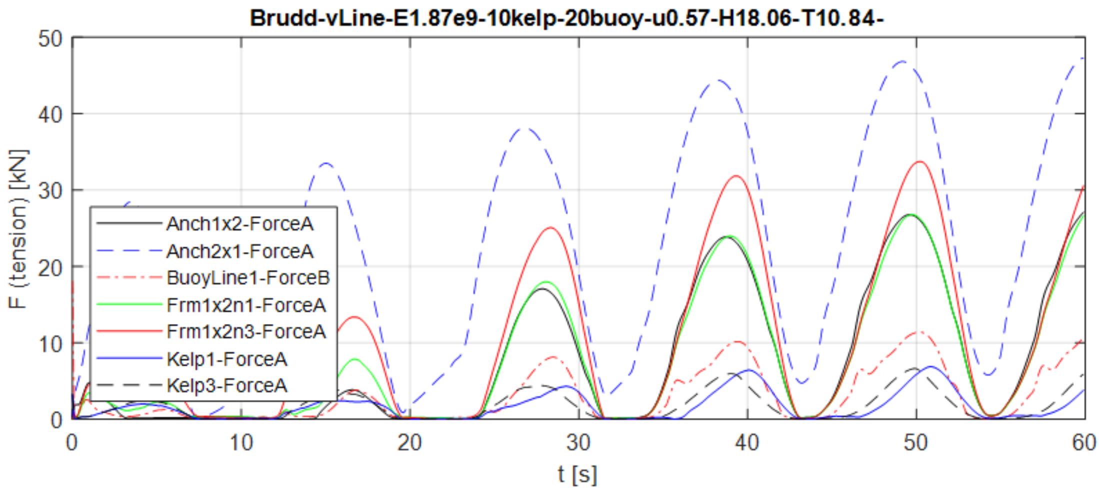
E : Test rig at Klovningen – simulation results from FhSim

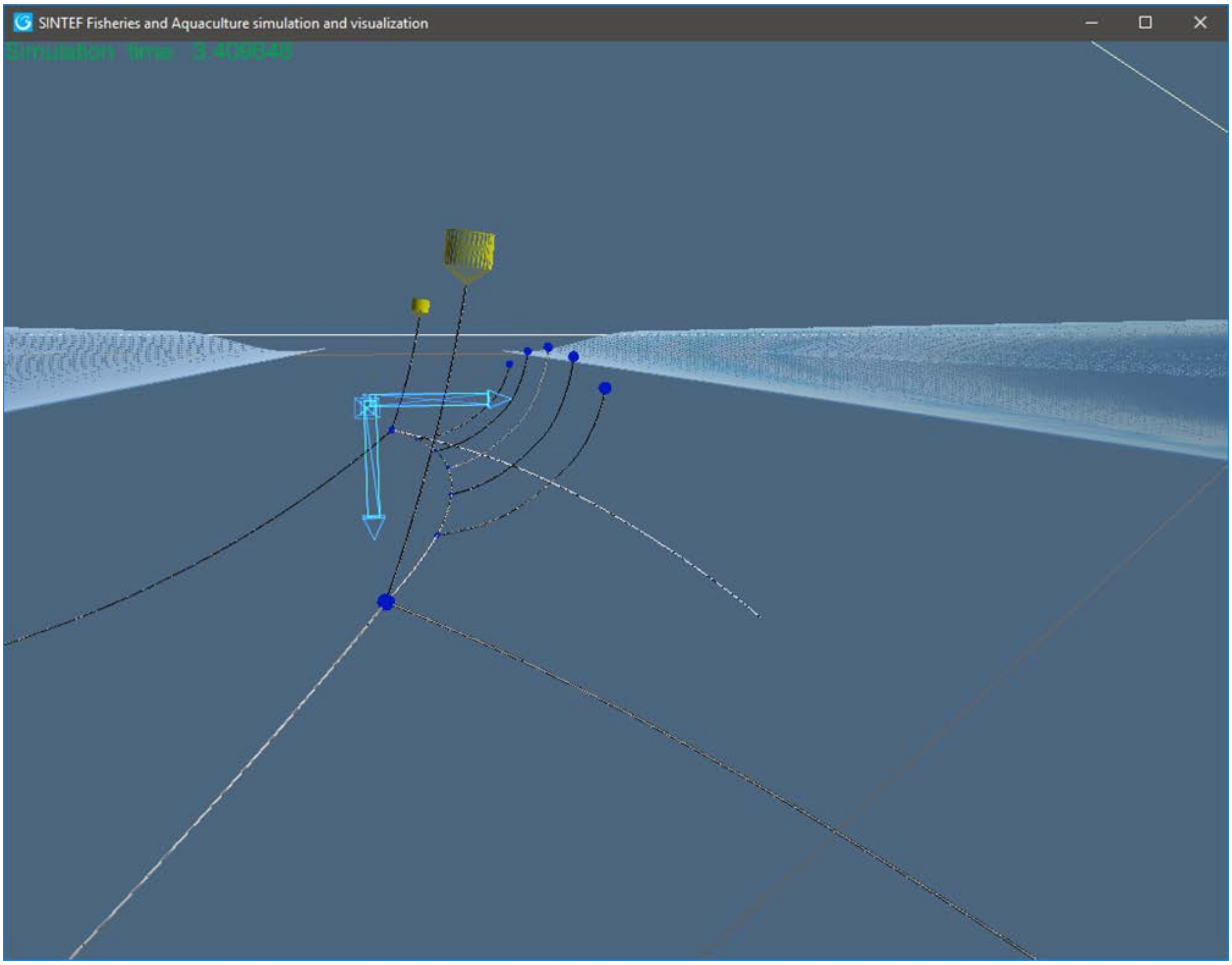
Results from simulation of vLine-concept, maximum tension in mooring lines (kN) in ULS (Ultimate Limits State) condition:



Results from simulation of vLine-concept, maximum tension in mooring lines (kN) in ALS (Accidental Limits State) condition:



Visualisation of vLine-concept in extreme wave condition:



F : Dimensioning of test rigs for Klovningen and Orstranda

Tabell 1: Dimensjonerende krefter i bruddgrensetilstand / ULS – Ultimate Limit State - Klovningen

Komponent	Krefter fra FHSim [tonn]	Dim. krefter inkl lastfaktor (1,15) [tonn]	MBL tau (3,0) [tonn]	MBL kjetting/sjakkel/ koblingsløkke (2,0) [tonn]	MBL brukt kjetting (5.0) [tonn]
Ankerliner	4,8	5,5	16,6	11,0	27,6
Rammetau	4,8	5,5	16,6	11,0	N/A
Bøyeline	2,7	3,1	9,3	6,2	N/A
Dyrkingsline	0,9	1,0	3,1	2,1	N/A

Tabell 2: Kapasitetskontroll av komponenter - Klovningen

Komponent	Dim. krefter [tonn]	Krav til MBL [tonn]	Valgt komponent [MBL]	Utnyttelses -grad	Beskrivelse
Anker	5,5	N/A	N/A	0,55	Ploganker 500kg for sandbunn, holdekraft ca. 20 ganger vekt
Ankerliner - tau	5,5	16,6	25,7	0,64	3-Slått Megaline - 40mm
Ankerliner - kjetting	5,5	27,6	40	0,69	28mm ankerkjetting, brukt
Ankerliner - sjakler	5,5	11,0	40	0,28	Fortøyningssjakkel, Gunnebo, MBL 40t
Ankerliner - løkke	5,5	11,0	68	0,16	Ring 32.0.6 Alloy Galvanisert (32mm, MBL 68t)
Rammetau-sjakler	5,5	11,0	40	0,28	Fortøyningssjakkel, Gunnebo, MBL 40t
Rammetau	5,5	16,6	16,8	0,99	3-Slått Megaline - 32mm
Bøyeline	3,1	9,3	16,8	0,55	3-Slått Megaline - 32mm
Bøyeline - sjakkel	3,1	6,2	6,5	0,96	Fortøyningssjakkel, Gunnebo, MBL 40t
Dyrkingsline	1,0	3,1	4,5	0,69	3-Slått Megaline -16mm

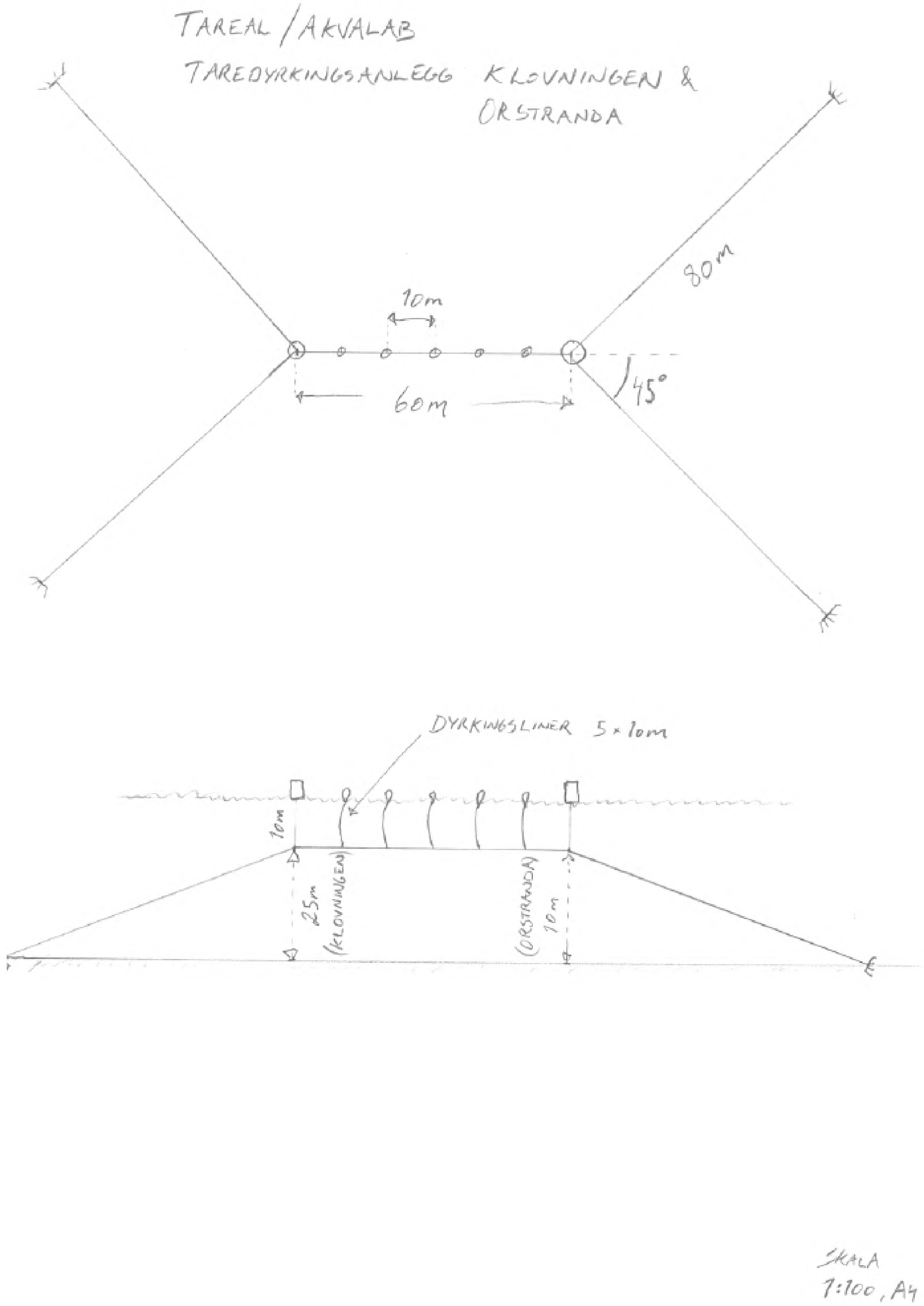
Tabell 3: Dimensjonerende krefter i bruddgrensetilstand / ULS – Ultimate Limit State - Orstranda

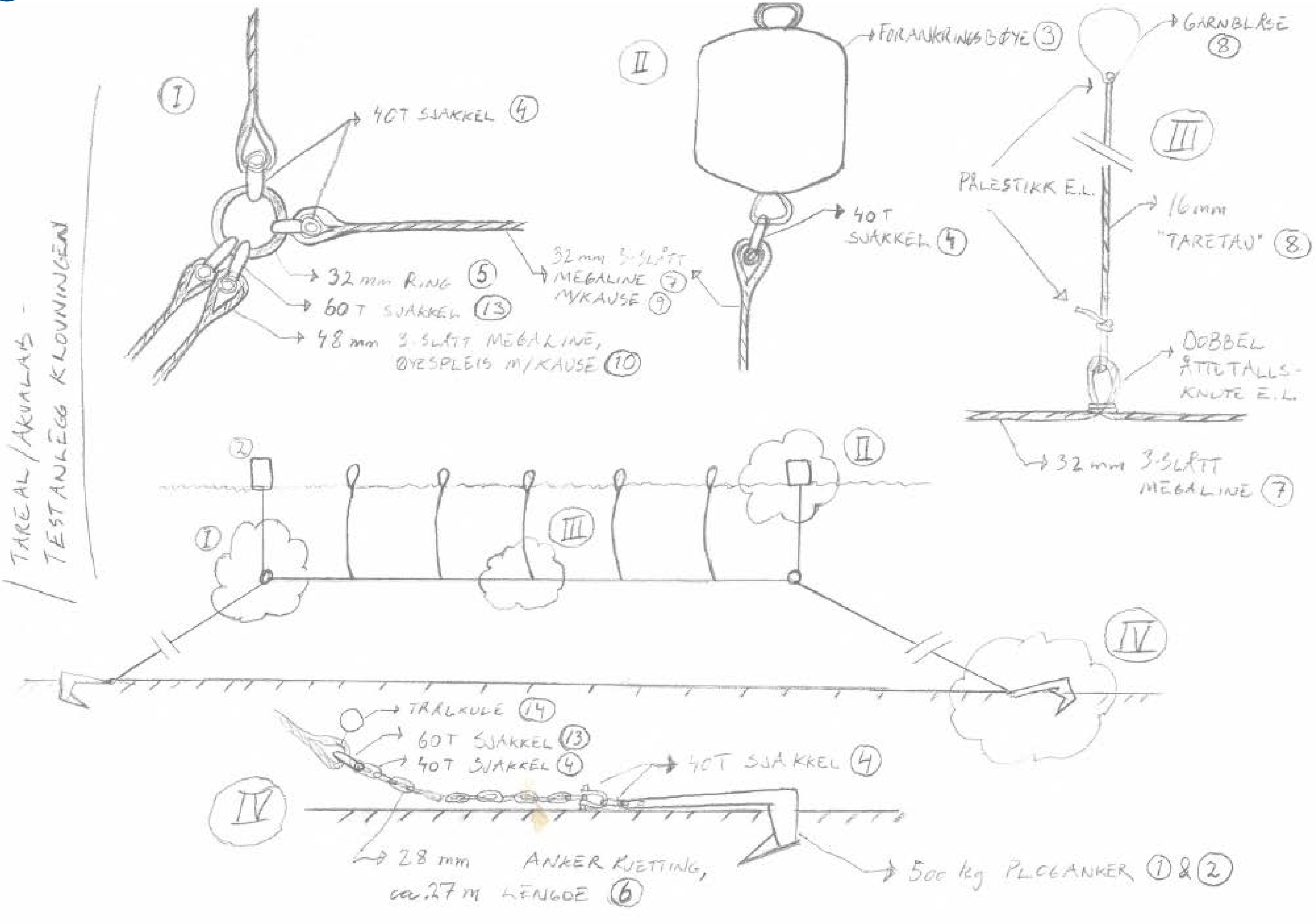
Komponent	Krefter fra FHSim [tonn]	Dim. krefter inkl lastfaktor (1,15) [tonn]	MBL tau (3,0) [tonn]	MBL kjetting/sjakkel/ koblingsløkke (2,0) [tonn]	MBL brukt kjetting (5.0) [tonn]
Ankerliner	1	1,2	3,5	2,3	5,8
Rammetau	0,8	0,9	2,8	1,8	N/A
Bøyeline	0,7	0,8	2,4	1,6	N/A
Dyrkingsline	0,25	0,3	0,9	0,6	N/A

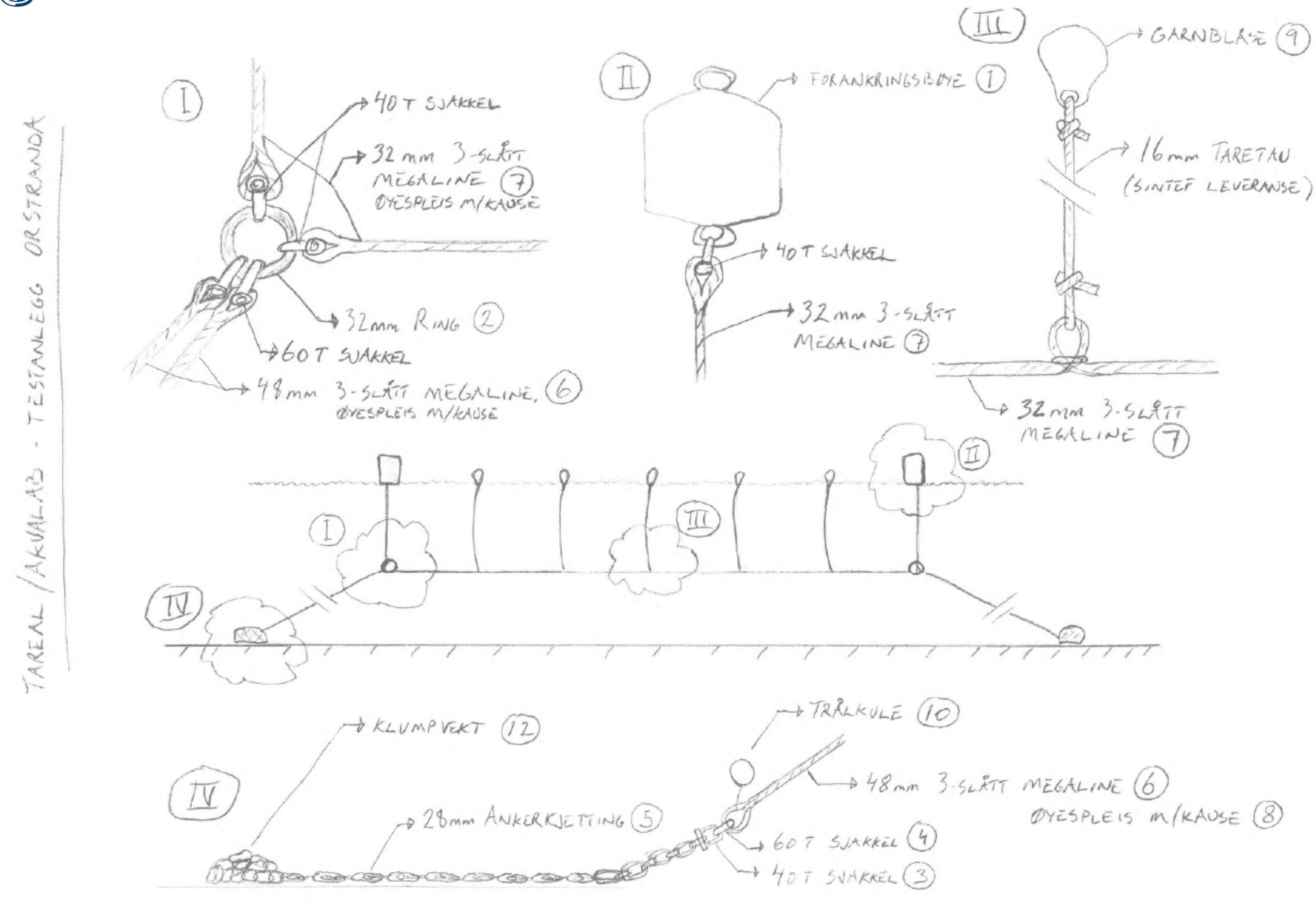
Tabell 4: Kapasitetskontroll av komponenter - Orstranda

Komponent	Dim. krefter [tonn]	Krav til MBL [tonn]	Valgt komponent [MBL]	Utnyttelses-grad	Beskrivelse
Anker	1,2	1,5*	1,5	1,00	Klumpvekt 1,5 tonn neddykket vekt, antar friksjon
Ankerliner - tau	1,2	5,8	36,6	0,16	3-Slått Megaline -48mm
Ankerliner - kjetting	1,2	5,8	40	0,14	28mm ankerkjetting, brukt
Ankerliner - sjakler	1,2	2,3	60	0,04	Fortøyningssjakkel, Gunnebo, MBL 60t
Ankerliner - løkke	1,2	2,3	68	0,03	Ring 32.0.6 Alloy Galvanisert (32mm, MBL 68t)
Rammetau-sjakler	0,9	1,8	40	0,05	Fortøyningssjakkel, Gunnebo, MBL 40t
Rammetau	0,9	2,8	16,8	0,16	3-Slått Megaline -32mm
Bøyeline	0,8	2,4	16,8	0,14	3-Slått Megaline -32mm
Bøyeline - sjakkel	0,8	1,6	40	0,04	Fortøyningssjakkel, Gunnebo, MBL40t
Dyrkingsline	0,3	0,9	4,5	0,19	3-Slått Megaline -16mm

G : Sketches of test rigs at Klovningen and Orstranda




TAREAL / AKVALAB - TESTANLEGG KLOVNINGEN
I
40T SJAKKEL (4)
32 mm RING (5)
60 T SJAKKEL (13)
48 mm 3-SLÅTT MEGALINE, ØYESPLEIS M/KAUSE (10)
32 mm 3-SLÅTT MEGALINE (7) M/KAUSE (9)
II
FORANKRINGSBØYE (3)
40 T SJAKKEL (4)
GARNBLÅSE (8)
III
PÅLESTIKK E.L.
16 mm "TARETAU" (8)
DOBBEL ÅTTETALLS-KNUTE E.L.
32 mm 3-SLÅTT MEGALINE (7)
IV
TRÅLKULE (14)
60T SJAKKEL (13)
40T SJAKKEL (4)
40T SJAKKEL (4)
28 mm ANKER KJETTING, ca. 27 m LENGDE (6)
500 kg PLOGANKER (1) & (2)


TAREAL / AKVALAB - TESTANLEGG ØRSTRANDA
I
40 T SJAKKEL
32 mm 3-SLÅTT MEGALINE (7) ØYESPLEIS M/KAUSE
32mm RING (2)
60 T SJAKKEL
48mm 3-SLÅTT MEGALINE, (6) ØYESPLEIS M/KAUSE
II
FORANKRINGSBØYE (1)
40 T SJAKKEL
32 mm 3-SLÅTT MEGALINE (7)
III
GARNBLÅSE (9)
16mm TARETAU (SINTEF LEVERANSE)
32 mm 3-SLÅTT MEGALINE (7)
IV
KLUMPVEKT (12)
28mm ANKERKJETTING (5)
TRÅLKULE (10)
48mm 3-SLÅTT MEGALINE (6)
ØYESPLEIS M/KAUSE (8)
60 T SJAKKEL (4)
40 T SJAKKEL (3)