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Offshore Aquaculture: Development, building and testing of a deep water mooring system

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Öryggi, umhverfi & erfðir

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NORA Final Report

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Tækniþróunarsjóður

Skýrsluágrip Matís ohf
Icelandic Food and Biotech R&D

Report summary

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Titill / Title	**Offshore Aquaculture:** ***Development, building and testing of a deep water mooring system*** / Úthafseldi: Þróun, smíði og prófanir á bólfærum fyrir eldi á opnu hafi		
Höfundar / Authors	Helga Gunnlaugsdóttir, Sophie Jensen, Gunnar Þórðarson		
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Ágrip á íslensku:	Áherslur á heilsusamleg og örugg matvæli hafa ýtt undir neyslu sjávarfangs. Sömuleiðis hafa auknar kröfur varðandi sjálfbæra nýtingu sjávarfangs ýtt undir eldi og ræktun í stað veiða á villtum tegundum. Takmarkað pláss á strandsvæðum hamlar hins vegar aukinni eldisframleiðslu í sjó á heimsvísu. Því er búist við að fiskeldi og ræktun á sjávarfangi muni í auknum mæli færast úr skjóli flóa og fjarða og meira út á opin hafsvæði. Sú breyting mun gera auknar kröfur til búnaðar til úthafseldis þar sem vinna þarf á meira dýpi og takast á við átök sem úthafsalda og hafstraumar valda. Steypuklumpar og dragakkeri eru hefðbundinn búnaður við eldisframleiðslu sjávarfangs en eldisframleiðendur leita nú að öruggari og ódýrari aðferðum til að festa búnað sinn við sjávarbotninn. Steypuklumpar og dragakkeri henta illa sem akkeri þar sem þau eru dýr og þurfa að vera mjög þung til að duga til notkunar á opnu hafi, sömuleiðis þurfa þau mikið pláss þar sem þau þola illa lóðrétt átök frá umhverfi og/eða þjónustubátum. Nota þarf stór skip með öflugan búnað til að að koma þeim fyrir langt frá ströndu og það er mjög kostnaðarsöm aðgerð. Tæknistál ehf. hefur þróað neðansjávarbor sem byggir á nýrri tækni sem festir létt skrúfakkeri við hafsbotninn, allt niður á 70 metra dýpi, án aðstoðar kafara. Verkefnið var unnið í samvinnu við Matís ohf., Siglfirðing ehf., Ocean Rainforest spf., Offshore Shellfish Inc., SINTEF MRB (R&D) og að hluta fjármagnað með styrk frá Tækniþróunarsjóði og NORA. Borinn er léttur, um 900 kg að þyngd, og byggir á þríhindri grind með þremur skrúfborum á hverju horni sem festir hann við sjávarbotninn. Síðan er skrúfakkeri, allt að fjögurra metra langt, borað niður í hafsbotninn með áfastri þjónustulínu. Vegna þess hve borinn er léttur er mögulegt að notast við hefðbundna þjónustubáta við eldi/ræktun, til að koma akkerum fyrir. Í samanburði við hefðbundin akkeri, s.s. steypuklumpa og dragakkeri, þykja slík borakkeri umhverfisvænni, ódýrari og þola miklu betur lóðrétt átak og þurfa því mun minna pláss fyrir eldi/ræktun. Slíkir eiginleikar eru mikilvægir fyrir eldi/ræktun í sjó en ekki síður fyrir aðra notkun eins og fyrir flotbryggjur eða bólfæri. Borakkerið sem þróað var í verkefninu hefur staðist ýmsar átaksprófanir en það var líka prófað í kræklingarækt við raunaðstæður fyrir opnu hafi í 6 mánuði í Eyjafirði. Prófanir stóðu yfir um vetratíma við verstu aðstæður og sýndu að akkerin héldu fullkomlega og stóðust álag mun betur en hefðbundin akkeri (steypuklumpar) gerðu á sama tíma. Markaðssetning á vörum og tæknilausnum sem þróaðar voru í verkefninu er komin vel á veg.		
Lykilorð á íslensku:	*Úthafseldi, neðansjávarbor, bólfæri, skrúfakkeri, tæknilausnir*		

Skýrsluágrip Matís ohf
Icelandic Food and Biotech R&D

Report summary

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Summary in English:	With ever increasing seafood consumption and greater environmental concerns for healthier and safer products, the demands on aquaculture production are rising. Limited space for suitable aquaculture sites along coastal zones is now recognised worldwide as a serious limitation for this important industry. The farming or cultivation of seafood is therefore expected to shift increasingly from sheltered fjords and bays to more exposed offshore culture sites. This expansion offshore, away from the visibility of coastal communities, means installing and anchoring aquaculture infrastructures at greater water depths in rough sea. Thus, in order to eliminate the logistic difficulties imposed by transporting and positioning heavy deadweight concrete anchors or drag-anchors offshore, aquaculture operators are seeking more cost-effective and practical mooring solutions like deep water drills using light-weight anchoring systems. Compared to traditional fish farming in sheltered fjords and bays, offshore aquaculture gear requires a much greater holding power as it is highly exposed to considerable physical forces e.g. by waves and currents. One of the remaining challenges for this offshore expansion is the costly installation of heavy concrete or drag-anchors to hold the aquaculture infrastructures at considerable water depths. Producers are therefore looking for more cost-effective and reliable mooring systems that can be rapidly and easily installed, to meet the increased biomass potential. Taeknistal Inc. has developed a new technology to fasten light-weight helical screw anchors into the seabed, at water depths up to 70 meters below surface, without the assistance of divers. The project was carried out in collaboration with Matis Inc., Siglfirdingur Inc., Ocean Rainforest spf., Offshore Shellfish Inc., SINTEF MRB (R&D) and partly financed by grants received from the Technology Development Fund in Iceland and NORA. An innovative drill machine was specially developed for installing helical screw anchors into the seabed. The submersible structure consists of a triangular drill frame with three small drills, using helical screws that are fixed to each corner of the triangle at the bottom of the drill unit. This drilling machine has the advantage of being light-weight, approximately 900 kg, and can be managed by an ordinary aquaculture service vessel. Compared to the traditional anchor types, such as concrete blocks or drag-anchor, the helical screw anchors are more environmentally friendly, less expensive and more resistant to vertical tension. These are all important factors in aquaculture, especially offshore where one can expect high waves and strong currents, in addition to the tension imposed by the larger service vessels when they are attached to the aquaculture lines. Managing the innovative drill machine was tested at open sea and the holding power of the anchors was tested in actual conditions during six winter months, where the screw anchors were drilled into the seabed at an offshore aquaculture site at Eyjafjordur (North Iceland). The results from this test demonstrated that the screw anchors have a holding capacity superior to that of traditional anchors which minimises the loss of crop, and reduces the environmental impact. Marketing of the products and the technical solutions developed in the project is well under way.
English keywords:	*Offshore aquaculture, deep-water drill, helical screw anchor, mooring system*

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Contents

THE PROJECT

The concept of the project was established in 2009 when mussel farmers in Northern Iceland, briefed their needs for reliable anchors to the machine shop company, Taeknistal Inc. The mussel farmers were at this time using natural stones or concrete blocks as anchors, which are expensive, cumbersome and very unreliable. This indicated that there was a need for innovative technology which would allow sustainable mussel farming to be carried out at exposed culture sites in open oceanic waters. Taeknistal Inc. contacted the Icelandic Food and Biotech R&D Company Matis, which took the lead to apply for research grants to fund the development of an innovative mooring technology that could withstand considerable physical forces and would also increase the productivity of the available culture area and minimise the loss of crop. Further investigation revealed that as the demand for shellfish continues to grow all over the world, limited space along the coastal zones for suitable aquaculture sites is recognised worldwide as a serious problem for this important industry. Therefore there is clearly an existing need and considerable marketing opportunities for new technical solutions that would enable aquaculture to be carried out offshore.

Figure 1. The drilling machine

The objectives

The main goal of this project was to develop a deep water drill and matching anchors suitable for offshore aquaculture, which would solve the above mentioned problems and conflicts in addition to giving the industry a huge opportunity for expansion and growth.

The products generated in this project are:

- A deep water mooring system which consists of innovative machinery i.e. a deep water drill and matching anchors, that can withstand considerable physical forces, are easy to operate, increase the productivity of mussel culture areas, minimise loss of crop, and reduce environmental impact
- A new technology for drilling anchors directly into the seabed at exposed offshore aquaculture sites without the aid of divers
- Effective incorporation of the new technologies into the existing equipment (long-lines, droppers etc.) for submerged mussel farming

The project partners

The project partners originate from four different countries and thus represent trans-national research efforts and a full list of partners is presented in Table 1 below. The partners are a combination of research and development (R&D) companies and small and medium-sized enterprises (SMEs), which provided a balanced match of technological skills, industrial objectives as well as market access related to the prospective outputs of the R&Ds. The SME partners had complementary business interests, to provide a rapid route for the developed technology onto the market. Each partner in the project had a specific role to play in the completion of the work and the exploitation of its results.

Table 1. Project partners

Organisation	Address	Land
Matis (R&D)	Vinlandsleid 12, IS-113 Reykjavik	Iceland
Siglfirdingur Inc. (SME)	Granugata 5, IS-580 Siglufjordur	Iceland
Taeknistal (SME)	Eyrartrod 8, IS-220 Hafnarfjordur	Iceland
Ocean Rainforest spf. (SME)	Niels Finsensgota 10 - P.O. Box 195 - FO-110 Torshavn	Faroe Islands
Offshore Shellfish Inc. (SME)	Polfearn, Taynuilt, Argyll, PA35 1JQ,	Scotland, UK
SINTEF MRB (R&D)	Klaebuveien 153, N-7465 Trondheim,	Norway

To ensure efficient project management and organisation of the project a project Steering Board was established (Table 2), which was responsible for the coordination of technical and R&D activities as well as contractual and administrative activities.

Table 2. Project Steering Board

Navn	Organisation	Address	Land
Dr. Helga Gunnlaugsdottir*	Matis (R&D)	Vinlandsleid 12, IS-113 Reykjavík	Iceland
Mr. Hilmar Erlingsson	Taeknistal (SME)	Eyrartrod 8, IS-220 Hafnarfjordur	Iceland
Mr. Olavur Gregersen	Ocean Rainforest spf (SME)	Niels Finsensgota 10 P.O. Box 195 - FO-110 Torshavn	Faroe Islands
Mr. John Holmyard	Offshore Shellfish Inc. (SME)	Polfearn, Taynuilt, Argyll, PA35 1JQ	Scotland, UK

*Project leader/coordinator

Summary of the work carried out

The first project year involved development of the machinery i.e. a drill and matching anchors and the technology for drilling anchors directly into the seabed. This included design and conceptual development, as well as functional tests and usability evaluation of the first prototypes to verify their performance and modify them according to the outcomes (Jonsson, et al., 2011) (Johannsson, 2011). Based on the specifications given in the design work for the final modification of the prototype, a pilot drill was built. The testing of the machinery was carried out in cooperation with potential customers who performed functional- and usability evaluation tests (Thordarson, Hauksson, & Gunnlaugsdottir, 2012b). These tasks were identified to optimise the design and accordingly develop machinery suitable for submerged mussel farming at diverse ocean conditions. The work in the first year also included compilation of the existing knowledge and understanding of the specific requirements for submerged offshore mussel farming, along with shaping the marketing strategies (Ogmundarson, et al., 2011) (Sigurdson, Thordarson, & Hilmarsson, 2012).

In the second year installation and integration of the anchors to existing equipment used for submerged mussel farming and industrial validation was carried out (Thordarson, et al., 2012b). The work in the second year also consisted of preparation of promotional and demonstration material for marketing of the products from the project as well as a detailed marketing- (feasibility study) and business plan (Thordarson, Gunnlaugsdottir, & Hilmarsson, Business Plan (confidential), 2012). Innovative activities such as the management of Intellectual Property Rights (IPR) and exploitation of project results were on-going throughout the entire project.

WORK PERFORMED & ACHIEVMENTS OF THE PROJECT

This project involved designing and constructing a hydraulically powered drill system for fastening anchors into the seabed at exposed offshore aquaculture sites without the aid of divers. It was necessary to demonstrate that the drill could be controlled at offshore conditions and could drill down the anchor into the seabed and leave it there with a service line attached. The aim was to develop a drill with compatible anchors that could be drilled and screwed/fastened into the seabed, in one continuous operation. The challenge was to build anchors suitable for a hard seabed (e.g. composite seabed) that keeps the anchor locked into one position. Therefore, it was necessary to demonstrate how much physical force it would be able to withstand and whether it would be sufficient for offshore aquaculture, where high waves and strong currents can be expected. The drill was tested in several field trials on diverse surfaces onshore and those tests were successful. After considerable modifications and functional testing of the deep water drill an appropriate technical solution was found and a pilot drill and matching anchors were developed. The final offshore drill field tests were successful and the aim of designing and building a deep water drill powered by a hydraulic system that can be used to fasten anchors into the seabed at exposed offshore aquaculture sites without the aid of divers, was achieved. Furthermore, the deep water drill-machine ensures precise drilling and fastening/screwing of anchors directly into the seabed, it is transportable, adaptable and easy to install. The matching anchors stay locked into one position and provide superior vertical and lateral holding power.

The business concept

There is a big market around the world for reliable anchors that remain locked into one position and provide superior vertical and lateral holding power, especially in relation to offshore aquaculture. There are indications that the demand for these anchors will increase substantially in the near future due to increased demand for production and cultivation of seafood.

Today traditional drag-anchors such as concrete or stone blocks are used to hold the aquaculture infrastructure e.g. long-lines for mussel culture. These are unreliable, cumbersome and are fairly expensive to install.

Figure 2. Image of the drill machine

The business concept presented here involves the drilling of a helical anchor into the seabed, down to 70 meters depth under the water surface, in a cost-effective manner. The innovative technical solution developed in this project is based on the idea to build a deep-water drilling machine capable of attaching itself to the ocean floor by means of three corner drills as shown in Figure 2. This design makes the deep-water drill light (about 900 kg) and compact, and it can be precisely positioned at the selected site where drilling of the anchor is required. The main drill motor is placed in the middle of the triangular drill frame to which a light-weight helical screw anchor with an attached surface line (wire, rope or chain) is fastened (see Figure 2). When the drill location has been decided, the drill machine is lowered to the seafloor along with the hydraulic cables and fastened to the seabed with the corner drills. Finally, the helical screw anchor with the attached service line is drilled down up to four meters into the sediment. Once the screw anchor is securely fastened, it is released from the main drill motor, separating the drill machine from the screw anchor, and then the corner drill screws are unscrewed from the seabed. The machine is hauled up on board the boat again, leaving the anchor with the service line behind in the seabed and the service line can then later be connected to the aquaculture gear. This technical solution allows for the whole process to be performed in one operation (Jonsson, et al., 2011).

The submerged long-line diagram in Figure 4 illustrates the setup for an offshore mussel production line. The horizontal main line that supports the shellfish is tensioned by large corner floats, which are under tension due to heavy anchors located at each end. Traditionally the moorings are large concrete anchors weighing up to five tones, or drag-anchors weighing 250 kg or more, which are both unreliable since they can easily detach when exposed to strong forces.

Most commonly, they are pulled out of position by service vessels working on the mussel lines and tangle around slack long-lines. Thus, more secure anchorage is required in the mussel industry to withstand considerable physical forces observed in offshore environments. The new technology developed by Taeknistal Inc. can provide this and the idea is fully developed, but proprietors are investigating the company's future source of long-term revenue.

The product

Most of the world´s mussel farming is practiced within the more sheltered locations in fjords and bays, and protected from the strong forces of open sea. These farming locations use drag-anchors or concrete blocks that have a limited ability to withstand offshore forces and tension from service vessels. Although the resistance of the equipment is generally not as crucial for sheltered farming as it is for offshore or exposed locations, it is still important that the anchors are secure and well embedded.

Figure 3. Service boat Keilir with the drill machine on board

For deep sea offshore aquaculture it is essential that the anchors can withstand considerable vertical pull since horizontal pull calls for much longer distances between the anchors if they are not heavy enough. A good example of the way long-line geometry influences its flexibility is the ratio of the length of the anchor line to the total depth. Fishermen tend to minimise the anchor weight so they can haul them up easily, but as a consequence, they must use a 3:1 anchor line to depth ratio in order to prevent the vertical forces from causing the anchor to be dragged along the surface of the seabed. However, the flexibility is more limited with a 3:1 ratio and it is more difficult to lift these lines to the surface for service.

Figure 4. Long-line with drag-anchors

In comparison, shorter anchor lines (1,5:1 ratio) are subject to more direct vertical forces which often result in the anchors dragging. To prevent this from occurring, and maintain a shorter distance between anchor points, which saves space on a lease, it is necessary to ensure that the anchors are highly stable and well embedded into the sediment. The new technical solution provides this valuable combination of flexibility, stability and ease of installation.

There are mainly two types of anchors used today, permanent and temporary, where the latter is usually used on ships and is pulled on board when it is in motion. Permanent anchors are mostly used in aquaculture for reliable long-term use. These anchors are usually dead-weights made of concrete or metal, heavy drag-anchors (plough anchors) and helical anchors that are drilled into the seabed. Most commonly used in Europe and the United States are the drag-anchors, along with the use of concrete blocks (Ogmundarson, et al., 2011). Both types may require heavy chains to resist instant pull on certain bottom types and for damping the torque from ocean waves or current, unlike the helical anchor which is capable of taking a direct force of pulling. An anchor drilled down four meters into a sandy bottom can, according to engineering calculations, withstand a torque of 20 to 50 tons depending on the sediment (Johannsson, 2011). In comparison, concrete blocks would need to be around 12 to 15 cubic meters (25-30 tons) in size in order to withstand the same force. Helical anchors are therefore well suited for all applications needing sound holding in the seabed, such as offshore mussel farming, algae farming, floating harbours or any other use that requires a secure anchor at depths down to 70 meters under the water surface.

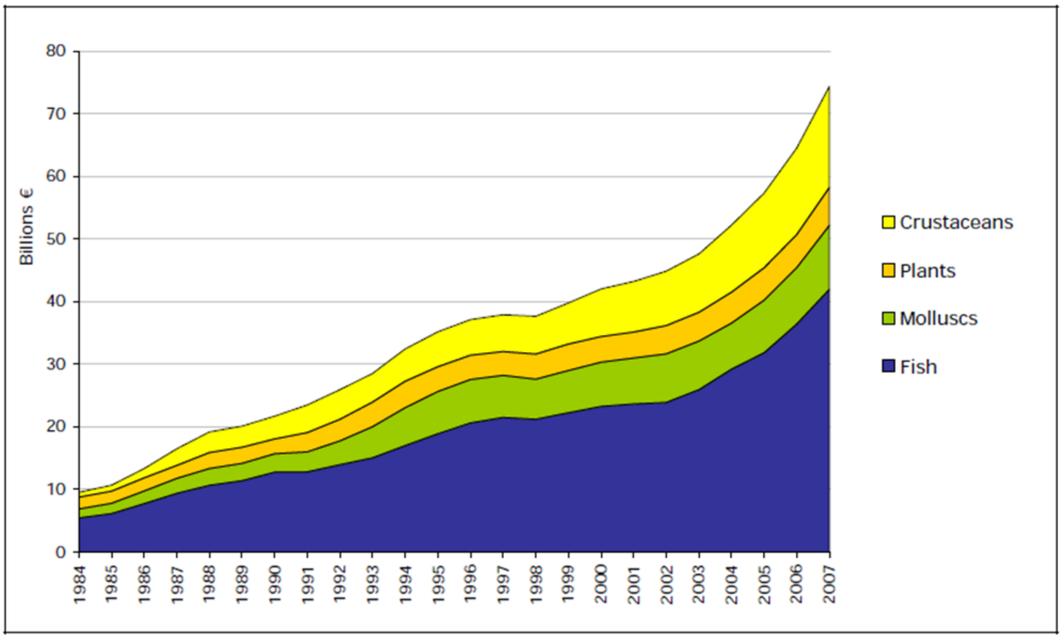
Offshore mussel culture can be an operation of large proportion using hundreds of anchors (Holmyard, 2012). Service and maintenance of anchors in these situations can be problematic and require high standards of strength and reliability, requiring efficient and durable equipment, which can be handled by normal service vessels (small boats). The technical solution developed in this NORA project seems to be among the best mooring products available to fulfil these offshore requirements and they can be installed in the seabed without diver assistance, or too much logistic expenditure.

The market

As global demand for shellfish continues to grow and there is a worldwide understanding that limited space for suitable aquaculture sites along coastal zones is now posing a serious problem for this important industry. As an answer to this already existing need in Europe, the goal of this project was to design a technical solution to facilitate expansion of offshore mussel culture by developing user-friendly equipment to drill reliable anchorage into the seabed, which can easily be integrated with the existing aquaculture equipment (e.g. long-lines in mussel culture etc.). In addition, the aim was to develop a new technology that would enable deep-water drilling of an anchor directly into the seabed with a service line attached to it, without the involvement of divers.

A high demand is expected for this new anchoring solution for aqua-farming equipment and an initial feasibility study revealed that this market is increasing (Ogmundarson et al., 2011).

The main market for the anchors are expected to be mollusc farmers, although market opportunities also exist to serve other kinds of aqua farming producers, like fish, algae and crustaceans. The global market trends for these products can be seen in Figure 5 in billions of euros.



Source: FAO (2008), elaborated by APROMAR

Figure 5. Global market size for aquaculture products in billions of euro´s

The new technique developed, will be the property of Hafbor©, which intends to maximise the profit opportunity and they expect to claim up to 20 to 25% share of the helical anchor market in the future. Since each drill machine can serve a fairly large area, the intention is not to mass produce the deep-water drill but instead the idea is to serve the needs of customers in different businesses. Hafbor's goal is therefore to explore a wide range of markets for its machine and to closely cooperate with parties serving all kinds of sea farming equipment in need of reasonably priced secure anchors, as well as float docks for farming and harbours. Besides serving the domestic market, Hafbor Inc. will work on forming a business relationship with parties providing services to customers worldwide. In addition, the company will systematically work on developing future technical solutions, addressing problems associated with drilling in different kinds of substrates, as well as problems with limited visibility underwater, which is a widely recognised problem.

THE PROGRESS OF INNOVATION

The present owner of the technical solution and products developed as part of the NORA project is Taeknistal Inc., a machine shop operated in Hafnarfjordur in Iceland. The business concept will be sold to the newly founded company, Hafbor Inc., which was established specifically for future operation of the business and will be operated from Siglufjordur, in Northern Iceland. Hafbor© sees great opportunities in Taeknistal's development of a cheaper and more reliable anchor for the aquaculture industry. The helical anchors are not only more reliable than existing solutions on the market, such as concrete blocks or drag-anchors, but are also price competitive.

Figure 6. The service boat "Keilir" with the drill machine on deck

To verify the performance and functionality of the innovative technical solutions developed, extensive field trials of the deep-water drilling machine and matching anchors on diverse surfaces (e.g. different seabeds) were carried out offshore (Thordarson, Hauksson, & Gunnlaugsdottir, 2012b) (Thordarson et al., 2012a) (Jonsson, et al., 2011). The first field trials were carried out in Siglufjordur harbour by drilling several helical screw anchors down 3 meters into sandy seabed soil. These field trials showed that it was easy to screw the anchors down, and the holding power tests revealed that the anchor endures at least 9 tons, without any signs of coming loose (Jonsson, et al., 2011). Additional offshore testing of the anchors´ holding capacity was carried out by pulling with full force of a boat. The anchors were at about 20 meters depth under the water surface with a rope (around 50 meters) attached to them and when the rope was fully stretched the engine was given full force (2300 rpm) i.e. around 750 horsepower. According to the boats manufacturer this type of boat and engine will result in between 18 to 20 tons of torque. An underwater camera showed that the anchors in the seabed did not move as a result of this pull test (Thordarson et al., 2012a) (Thordarson, Hauksson, & Gunnlaugsdottir, 2012b). In addition, a civil engineer from Siglufjordur Engineering calculated the holding power of the anchors and their durability (Johannsson, 2011).

Figure 7. Drilling test at Siglufjordur harbour

The field trials also included installation of the developed anchors using the deep-water drill and integration of the anchors with the existing equipment i.e. offshore mussel culture long-lines in Eyjafjordur (North Iceland) in cooperation with the Icelandic mussel farm Skelfelagid (Thordarson et al., 2012a). In order to test the mooring system for submerged mussel farming in a real life situation, the performance of the anchors connected to mussel culture long-lines with 3-4 tons of mussels in socks attached to the lines at an exposed offshore culture site was monitored over a 6 month period (Thordarson, Hauksson, & Gunnlaugsdottir, 2012b). On January 15th 2012 a team from Taeknistal, Matis and Siglfirding drilled four Hafbor© screw anchors into the seabed in Eyjafjordur, West of Hrisey, using the deep water pilot drill built in the project.

Five weeks later on the 21st and 22nd of February employees from the Skelfelagid mussel farm attached mussel socks/droppers to a long-line that had been fastened to the anchors in the seabed in the drilling process and hence, integrated the anchors with the existing equipment at exposed offshore mussel culture site. Skelfelagid monitored the performance of the fully integrated mooring system for mussel farming in Eyjafjordur periodically for 6 months. The most extensive investigation was carried out on the 12th of August 2012 when the system was inspected by a diver and the observations made during the dive were documented using an underwater camera. The inspection revealed that after six months in the seabed, all of the Hafbor© screw anchors as well as the mussel socks attached to them in February 2012 remained firmly installed and unmoved. Only minor surface rust of some parts was observed but the anchor lines showed no sign of wear or tear. In contrast, several 3.000 kg concrete and blast rock deadweight anchors attached to mussel lines at the same culture site had been shifted and dragged along the seabed. The conclusions from the long-term evaluation of the Hafbor© screw anchors are that they can withstand considerable physical forces, are easy to operate, minimise loss of crop, and reduce environmental impact (Thordarson et al., 2012a).

DISCUSSION & CONCLUSIONS

The results of the offshore field tests and the technological development, involving finding suitable solutions for drilling anchors directly into the seabed without the assistance of divers, have shown that the drill machine developed in this project can easily drill 20 to 30 cm diameter helical screw anchors at least four meters into the seabed. Furthermore, functional and holding capacity tests revealed that one anchor can endure at least 18 to 20 tons, without any signs of coming loose. Calculations estimated the endurance between 12 and 25 tons force, depending on seabed characteristics, during a vertical pull. Problems regarding getting the machine down to the seabed were solved and adjustments between the hydraulic system of the boat and the drilling motor were made to obtain maximum power during drilling. Problems regarding cameras were solved and suitable cameras allow monitoring of the drilling procedure at considerable depth (at least 25 meters) under water.

Figure 8. Inventor, Erling, at the helm of the drill machine

The last offshore field drill test, recorded on digital video, was successful and the aim to design and build a deep water hydraulically powered drill that can be used to fasten anchors into the seabed at exposed offshore aquaculture sites without the aid of divers was achieved. Moreover, the drill-machine ensures precise drilling and fastening/screwing of anchors directly into the seabed, it is transportable, adaptable and easy to install. The matching anchors stay locked into one position and provide superior vertical and lateral holding power. The inventor has applied for a patent for an essential technical part of the drill machine and this application presently has a patent pending status in 22 countries for the technical solutions developed.

The main achievements to the state-of-the-art and products of this NORA project, that can have a positive impact on the competiveness of aquaculture in Nordic countries:

- Development, building and testing of an innovative machinery, i.e. hydraulically powered drill machine and matching screw anchors, that can be used to install anchors into the seabed at exposed offshore sites and thus enable aquaculture to be carried out in open oceanic waters
- Development of a new approach for installing screw anchor moorings without the assistance of divers water depths up to 70 meters
- A deep water drill machine that is lightweight (750-900 kg) and portable, hence it can be operated from any vessel with a hoisting device stable enough to support 1000 kg i.e. most service boats in the aquaculture industry are suitable for the installation of the developed offshore mooring system
- A new technology has been developed that offers an easy way to install screw anchors both in deep and shallow water with high positioning accuracy, cost efficiently and a low environmental impact
- Screw anchors that have good holding power and can withstand considerable physical forces, these screw anchors can be custom designed to meet individual requirements of different applications and necessary pullout strength. In the mussel industry the superior holding power of these anchors will increase the productivity of the available mussel culture area and minimise the loss of crop. It will also improve returns per unit of mussel culture line, which will reduce production cost and make the Nordic mussel industry more competitive on the global market
- Production and sales of the deep water drills and anchors outside of Nordic countries
- Submerged offshore mussel culture opens possibilities for Nordic mussel and/or aquaculture farmers to increase production, giving them the ability to expand into new markets

BIBLIOGRAPHY

Holmyard, J. (2012, Feb. 10th). Number of anchors for aquaculture. (G. Thordarson, Interviewer)

Johannsson, T. (2011). *Structural Engineering Evaluation for Helical screw Anchors.* Siglufjordur: Verkfraedistofa Siglufrjardar.

Jonsson, E., Erlingsson, H., Jörgensen, V., Thordsteinsson, H. S., Hauksson, O., Gudmundsson, S., et al. (2011). *Development, building and tests of deep water mooring system for Offshore Aquaculture.* Reykjavík: Matis - 34-11.

Lindell, S. (2010). *Opening the Ocean to Mussel Farming wth Robust Low-cost Engineering.* Boston: Marine Biological Laboratory, University of Massachusetts.

Ogmundarson, O., Holmyard, J., Thordarson, G., Sigurdsson, F., & Gunnlaugsdottir, H. (2011). *Report from the initial feasibility study & market requirements for the innovations from the project.* Reykjavik: Matis 29-11.

Sigurdson, F., Thordarson, G., & Hilmarsson, I. (2012, Nov.). Sintef - Concept for strategic business development. *LOBSTER (confidential report)*. Reykjavik: Matis.

Thordarson, G., Erlingsson, I., Erlingsson, H., & Gunnlaugsdottir, H. (2012a). *Results from a long term industry validation of a new mooring system for offshore aquaculture.* Reykjavik: Mati 33-12.

Thordarson, G., Gunnlaugsdottir, H., & Hilmarsson, I. (2012). *Business Plan (confidential).* Reykjavik: Matis.

Thordarson, G., Hauksson, O., & Gunnlaugsdottir, H. (2012b). *First results from the long term industry validation of a new mooring system for offshore aquaculture.* Reykjavik: Matis 06-12.