Ecological design of scour protection for offshore wind power

Master's thesis in Industrial Ecology

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Cover: Offshore wind farm, photo courtesy of Svea Vind Offshore AB

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Abstract

The energy transition plays an important role in the work towards mitigating climate change and working towards a sustainable development. Wind energy is an energy source which holds a huge potential when it comes to providing energy from renewable energy sources. This can be applied to Sweden and neighbouring countries, as well as globally. There are two types of wind energy, onshore and offshore. On shore is based on land, while offshore is based in ocean areas. This report deals with offshore wind power.

Offshore wind turbines are installed in sea areas, and the foundations by currents standards are attached to the seabed. An important question to take into account when installing a new offshore wind farm is how the local marine wildlife might be affected. The currents cause the particles and sediment around the foundation to move, and these movements can create a hole-like structure in the sea bed against the foundation. This phenomenon of the sea bed close to the turbine moving, is called scouring. In order to prevent scouring, wind turbine foundations shall be installed together with a feasible scour protection. The foundation of the wind turbine as well as the scour protection has the ability to work as an artificial reef for the fish living in the area.

Svea Vind Offshore AB is currently developing offshore wind farms in the Baltic Sea, with the aim of contributing to sustainable development in as many parts of their projects as possible. At the request of Svea Vind offshore, the aim of this master's thesis is to investigate how local marine wildlife interact with different designs of scour protections, with the purpose of finding the alternative that has the highest positive effect on local marine wildlife. The operation of wind turbines also emits low frequency underwater noise, which is taken into account in the study.

The study included three different experiments. The first one tested fish behaviour in an environment with noise and scour protection, in comparison to a quieter environment without scour protection. This experiment included testing three different designs of scour protections; one made out of small to medium-sized rocks, one made with concrete bricks, and one made with geotextile sand containers. Atlantic cod, shorthorn sculpin and black goby were selected as fish species for the experiments. The second experiment involved testing the scour protections against each other, without adding any turbine noise, and observing which one was the one preferred by Atlantic cod and shorthorn sculpin. The third experiment tested if the scour protection that was shown to be most preferred by the fish, was efficient in reducing scouring from currents. This was carried out by the use of a hydraulic flume machine that generated artificial currents.

Based on the results, the rocks scour protection may offer the most preferable environment for the Atlantic cod and shorthorn sculpin. This could be due to the fact that the scour protection resembles their natural habitat and provides shelter. The black goby did not show any clear preference for any of the three scour protections, which can be due to its natural hiding behaviour.

The comparison experiment of the scour protections did not demonstrate a clear preference from any species for one particular scour protection design, which may be explained by the low number of replicates for this part of the study. Moreover, the experiment with currents successfully highlighted the importance of scour protections in the offshore wind power farms, since they effectively prevented the wind turbine foundation against scouring. In summary, the results of the conducted experiments indicate the potential benefits of rocks scour protection.

Keywords: offshore wind power, wind turbine, wind farm, underwater noise, marine wildlife, currents, scouring, scour protection, behaviour study

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1

Introduction

This chapter presents the study's background, aim and objectives, research questions, delimitations and ethical aspects.

1.1 Background

In order to mitigate climate change, it is important to increase the access to renewable energy sources [2]. The COP28, which was the UN Climate Change conference 2023, addressed that the progress of climate action globally had previously been to slow, and that there is a need for countries to accelerate the work with climate change mitigation [4]. The conclusion also included a request to the governments to accelerate the energy transition, meaning that there is globally a need to switch energy sources from fossil fuels to renewable energy sources, for example, wind energy [4].

The wind energy has been acknowledged as an important source of energy in the process of mitigating climate change [4]. The are two main alternatives for wind power: onshore and offshore wind power [5]. In the last years, the wind power industry has been moving more offshore in order to take advantage of the wind speeds on the oceans to generate electricity [5]. A wind farm, which is comprised of several wind turbines assembled in one area, regularly goes through three stages [6]. The first stage is the construction of the wind farm, the second stage is the operational stage, and the third and final stage is the decommissioning [6]. Depending on the stage of the wind farm, fish might be affected differently. The construction stage normally takes a couple of days per wind turbine, and the operational stage lasts around 40 years [6].

During the operational stage, the wind turbines emit underwater noise that has a continuous character [6]. Fish that are stationary can be affected in various ways of new offshore wind farm installations. With regards to the underwater noise, fish generally have a hearing ability that is well-developed [7] [8]. In addition, how fish react to increased noise levels might thus vary in between species. The way the sound spreads is also affected by the conditions of the water and the character of the sea bottom environment [6].

When a wind turbine foundation is mounted on the seabed, the structure can cause local eddies and increased velocity of currents and waves in the area [9]. The quickly flowing water has the capacity to stir particles of sand and sediment, as well as transporting them aside from the foundation structure. This causes the creation of a hole around the structure. This phenomenon is called scouring [9]. To avoid scouring of the wind turbine foundations, it is important to install a suitable scour protection [10]. Scour protections of today are normally constructed out of rocks or boulders distributed around the foundation of the wind turbine. During the operational phase of a wind turbine, the foundations as well as the scour protections, come with the ability to act as an artificial reef structure that can accumulate the fish in the area [6]. The fish can have different reasons for seeking this type of structure, such as wanting an area for feeding, reproduction, or protection against possible predators. For the development of future offshore wind farms, it is therefore necessary to realise further research in order to optimise the design of scour protections [10], so that they can offer a suitable habitat for fish.

1.1.1 The project

Svea Vind Offshore is currently developing several offshore wind farms in the Baltic Sea, and there is an aim to contribute to the sustainable development in as many parts of each project as possible [11]. The wind turbines do expose the local marine environment to low frequency underwater noise that is around 30 Hz to 120 Hz [12]. The sound levels are to be found approximately between 87 and 137 dB with a distance of 100 meters from the wind turbine [13]. The scour protection can potentially reduce the impact on the local ecosystems by providing shelter for stationary fish and reduce altered movement of the sediment. Svea Vind Offshore intends to use the scour protection that is preferred by fish, in order to mitigate the impact on local marine wildlife in their projects. There is therefore the need for an assessment that looks into different types of scour protection alternatives, and how a scour protection should be constructed in order to minimise the impact on and offer suitable habitat for fish.

1.2 Aim and objectives

The purpose of this master's thesis is to investigate which scour protection is preferred by fish that live close or in an offshore wind power farm. The study includes testing three different designs of scour protection, together with underwater noise from wind turbines, and analysing which scour protection is preferred by fish.

The scour protection designs that are used in the study are: randomly distributed small to medium-sized rocks, piled bricks of concrete, and piled geotextile containers filled with sand. The aim is to further try the three designs and determine which one of them that minimises the impact on and offer suitable habitat for fish. The results of the study can be used in further research revolving offshore wind farms, as well as in assisting the offshore wind farm industry when it comes to decreasing the environmental impact during the operational stage.

1.3 Research questions

In order to determine which scour protection design that is most preferred by fish, the following research questions have been formulated:

1. Do fish prefer to stay in a less noisy environment with no scour protection or a noisy environment with scour protection?
2. If the fish choose protection, which of the scour protections, rocks, concrete bricks and geotextile sand containers, do they prefer under conditions of noise exposure?
3. Is the preferred scour protection effective in reducing scouring from underwater waves and currents?

1.4 Delimitations

The study only researches the marine wildlife during the operational phase of the wind farms, and the other phases are left out of the study. The study also only look at three specific fish species; Atlantic cod, shorthorn sculpin and black gobie, all representative for the marine wildlife in the Baltic Sea.

1.5 Ethical aspects

The study involves handling with living fish, and therefore several ethical aspects regarding the experiments with the fish need to be taken into account [14]. According to the Swedish Animal Welfare Act 2018:1192 and the Article 23 of the Directive 2010/63/EU, it is a legal requirement for people who use or participates in the use or care of animals used for research and education, as well as for people involved in planning animal experiments, to have an appropriate education in Swedish legislation, ethics and animal welfare. Moreover, when it comes to the handling of fish specifically, if having no previous qualifications, it is also mandatory to complete a course in laboratory animal science about fish. This is in order to also follow the Directive 2010/63/EU and the Swedish legislation about the protection of animals used in research.

2

Theory

This chapter gives a theoretical background for the study. It explains the needs for an energy transition and presents an overview of the offshore wind power industry. It further examines different offshore wind turbine foundations. It explains the phenomenon of scouring, what a scour protection is and how it may be designed. Lastly, the chapter also marks out what environmental impacts offshore wind power can cause to the living environment.

2.1 The energy transition and the offshore wind power industry

Enhancing the production of renewable energy is important to mitigate climate change [2]. The COP28 UN Climate Change conference, held by the end of 2023, concluded that the progress had previously been too slow when speaking of multiple areas of climate action [4]. The conference included more than 150 governments, and it denoted the finish of the first global stocktake of the efforts that had been made in order to reach the 1.5 ºC global warming goal made in the Paris Agreement [4]. The nations made decisions regarding how to speed up the climate mitigation actions in all areas by 2030. This included a call on the governments to accelerate the the energy transition. This highlights that there it is necessary for the nations to switch the energy sources from fossil fuels to renewable energy sources, such as solar power and wind power [4].

One of the agreements from the COP28 states that the renewable energy capacity must triple globally, and energy efficiency improvements shall double by the year 2030 in order to get on track for reaching the goal of the Paris Agreement [4]. Wind energy was in the final decision acknowledged as a crucial technology for mitigating climate change. The are two main alternatives for wind power, onshore, and offshore wind power [5]. Onshore wind power has been under use for over two thousand years, while the development of the offshore wind power industry is more recent. In recent years, the wind power industry has been beginning to move more offshore in order to take advantage of the wind speeds on the oceans and generate large scales of electricity [5].

Globally seen, there is currently an increase of wind power, both onshore and offshore [1]. In 2023, there was an increase of new installations by close to 50%, in comparison to the year before. There was an addition of 106 GW of onshore wind power and 10.8 GW of offshore wind power [1]. Figure 2.1 shows the historical development of new wind turbine installations over the last 20 years, in GW. The share of offshore wind power between the years 2004-2010 can be approximated to 1% of the total new wind turbine installations. For the years 2010-2015 the share can be approximated to 3% overall. Followingly, for the years 2015-2023 the share has been between 5-23%.

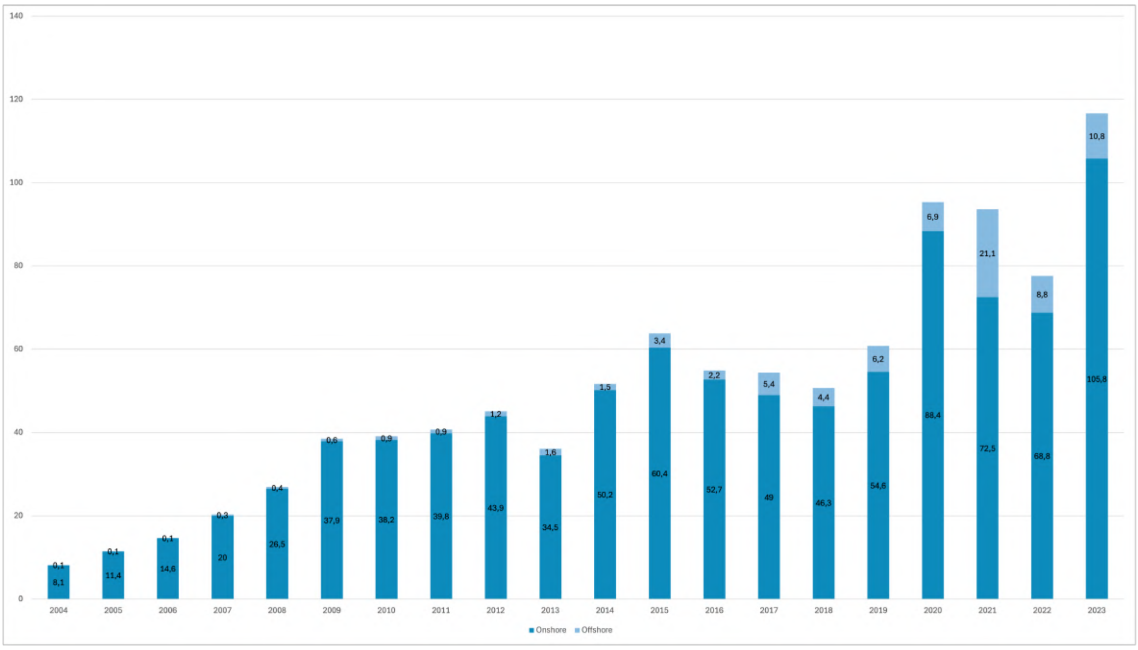

Figure 2.1: Historical development of new offshore and onshore wind turbine installations (GW). The illustration is made with data from the GWEC Global Wind Report from 2024 [1].

Offshore wind power accounted for 9% of the global wind power industry's new wind turbine installations in 2023. [15]. The current future predictions made by the Global Wind Energy Council [15] also point towards an even larger increase of wind turbine installations, both onshore and offshore over the coming years. The predictions say that with the planned growth rate of 28%, the annual additions in offshore wind energy are with high probability going to triple by the year 2028, counted from the levels of 2023. Altogether, between 2024 and 2028, a total of 138 GW of capacity for offshore wind is expected to be added. This is expected to occur with installations of approximately 27.6 GW per year. Figure 2.2 shows a global future prediction of new onshore and offshore wind turbine installations in GW.

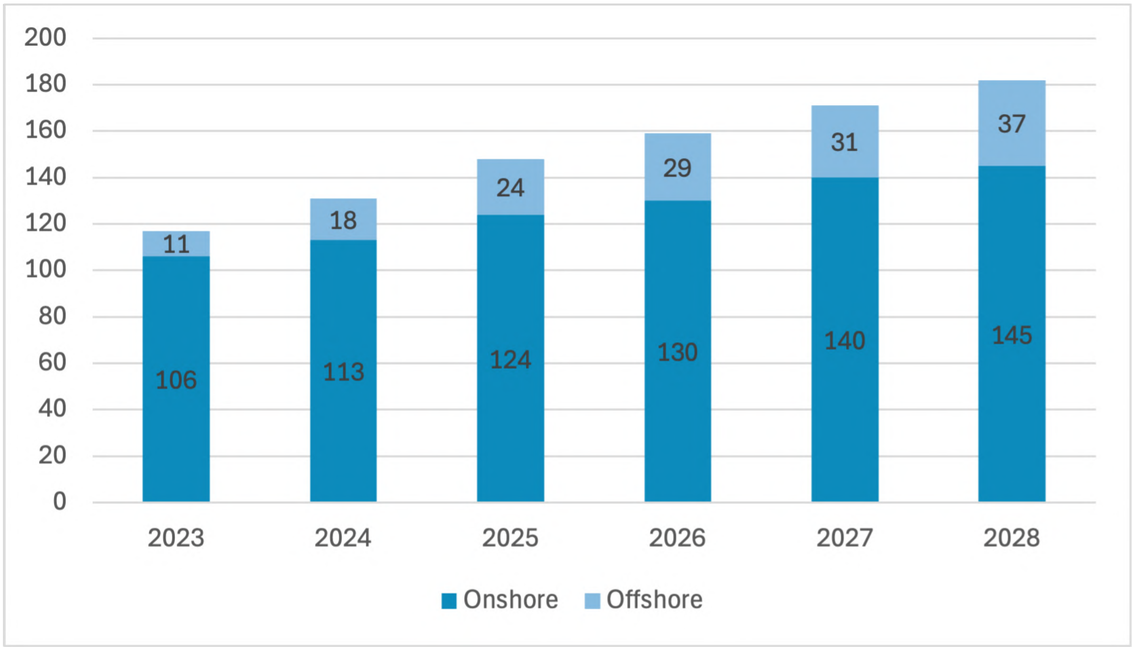

Figure 2.2: Future prediction of new wind offshore and onshore turbine installations (GW). The illustration is made with data from the GWEC Global Wind Report from 2024 [1].

The importance of offshore wind power as a potential energy source is increasing in Sweden in specific, as well as in the global context [6]. Several assessments have determined that there is a large potential for establishing more offshore wind power around Sweden, as well as in neighbouring countries around Sweden [2].

2.2 Offshore wind turbine foundations

The foundations of offshore wind power plants have until now mostly been established within the depths of 5-40 meters below the sea surface [2]. The development does however point towards offshore wind power plants at a deeper level as well, around 40-60 meters. The Baltic Sea has an average depth of 54 meters [16]. The main parts of an offshore wind turbine is the wind turbine itself and the foundation that establishes it [2]. It also includes an internal cable network that connects the wind turbine to a transformer platform, as well as connecting cables that leads the generated electricity from the ocean to land. This construction has to be resistant to large stresses such as waves, currents, strong winds, and in some cases, also ice [2]. These stresses are acting in addition to the own loads of the construction. Geological circumstances as well as water depth might also affect the wind turbine and its dimensioning [2].

The foundation of an offshore wind turbine is set under the water surface and its purpose is to carry the wind turbine by securing it to the sea floor [2]. A transitioning piece is often used where the foundation is attached to the turbine itself.

There are different ways to dimension the foundation of a wind turbine. The type of foundation that is used depends mostly on the local circumstances around the wind turbine [2]. It is therefore necessary that the location in which the offshore wind power turbine is to be installed is thoroughly investigated before a type of foundation is selected [2].

Monopile is a type of structure that consists of a steel cylinder that is knocked down deep in the sea bottom sediment [2]. These can have a diameter of 10-18 meters. Monopile foundations are normally constructed on softer sea bottom substrates, and suit on bottoms without underlying boulders or firm underlying layers. If drilling is used, this type of foundation can also be established on harder sea bottoms [2]. Monopile with a suction bucket is another type of foundation that is, similarly to the ordinary monopile foundation, also constructed with a steel cylinder [2]. This type of foundation is however attached with a suction cup closest to the sea bottom. The suction cup is attached by the creation of negative pressure. This technique might be used on more homogeneous and sandy bottoms, that are normally not to deep [2].

Gravity foundation is another type of offshore wind turbine foundation. This type of foundation stands on the sea bottom and holds up the wind turbine with the help of its size and weight [2]. It is normally made with a concrete caisson or steel container that is filled with ballast. This type of foundation is not used as frequently as monopile foundations, even if they are easy to use where they are feasible. This type of structure requires that the sea bottom has a good carrying capacity and that the depth is not too large. Offshore wind turbine foundations can also be constructed with jacket foundations [2]. These foundations are constructed with three or four piles, which are attached to the sea bottom. The attachment to the sea bottom is done either with the help of suction buckets or with smaller steel piles that are knocked down to the sea bottom [2]. These type of formations are normally used when constructing a wind turbine on a larger depth (larger than 40 meters), since the structure helps with allocating the loads over the construction. Figure 2.3 shows an illustration of the different offshore wind turbine foundation types.

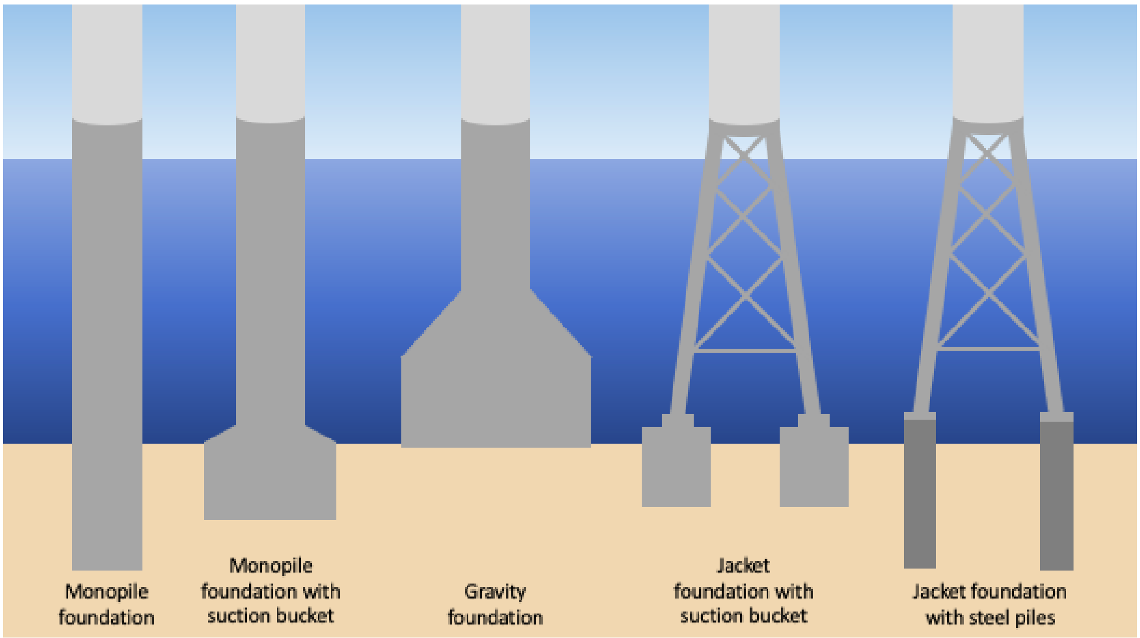

Figure 2.3: An illustration of different designs of foundations for offshore wind turbines. The image was created with inspiration from the report *Effekter av havsbaserad vindkraft pa marint liv* written by the Swedish research programme Vindval [2].

2.3 Scour protection for offshore wind farms

The phenomenon of the sea bottom changing around the foundation of the wind turbine is called scouring [10]. Offshore wind power plants are in many cases installed together with scour protection, which helps to prevent scouring and instability around the structures [10]. The purpose of installing a scour protection is to prevent that the sea bottom around the foundation experiences any changes over time [2]. Moreover, previous research has shown that using a feasible scour protection system in offshore wind power has the potential to reduce the effects from scouring with up to 92 % [10]. Installing a feasible scour protection is especially important to take into account when establishing new offshore wind farms in sea water with strong underwater currents [10]. Figure 2.4 shows a simplified illustration of a scour protection made with rocks.

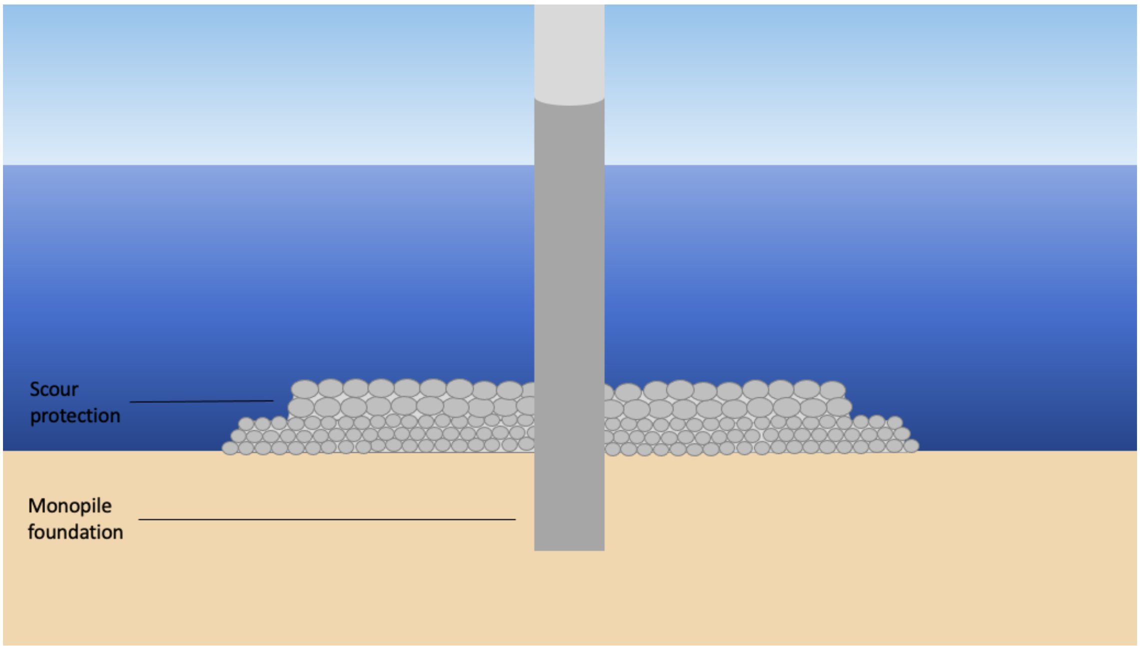

Figure 2.4: A simplified illustration of a scour protection for an offshore wind turbine with a monopile foundation. The image is made with inspiration from the paper *Riprap scour protection for monopiles in offshore wind farms* written by Esteban et al. [3].

The velocity of the surface water movement in the Baltic Sea is normally around 5-10 centimeters per second, but during storms it can get up to 50 centimeters per second [16]. Currents that occur closer to the sea bottom are normally slower than the currents in the surface water, and they usually have a velocity only a few centimeters per second [16].

Moreover, offshore wind farms come with a hard sea bottom environment that can work as an artificial reef, which is a type of reef structure formed by human activities [6]. It has been shown that this type of artificial reef structure has the possibility to accumulate fish. This applies to the wind power foundation as well as the scour protection that surrounds it [6]. Fish have several reasons for seeking the wind turbine foundations, such as acquiring an area for reproduction, feeding, or getting protection from any possible predators in the area [6]. Different fish species are generally affected in different ways. Some fish species could show clearly that they have a preference of being close to the structure, while other species might be more or less unaffected by it. This means that, under certain circumstances, establishing a new offshore wind farm comes with the possibility to favour the biodiversity in the area [6].

2.3.1 Different designs of scour protection

The need for scour protection systems in offshore wind power has been previously proved [10]. Furthermore, some designs are more frequently used than others when it comes to scour protection, and this is because of factors such as cost and availability of the materials [10]. Scour protections for offshore wind farms today most commonly consist of rocks or boulders [2]. This is due to their availability and low cost, compared to other alternatives [17]. Using a scour protection made of rocks does however require large amounts of rocks being placed on the sea bottom. The rocks that are used commonly have to be carried and transported from locations far away from the offshore wind farm [17]. The scour protections out of rocks are in many cases constructed out of two different layers, one bottom and filtering layer, and one top and armouring (protective) layer [10]. Considering the functionality of the two layers respectively, the sizing of the components of the layers normally differs, where the bottom layer consists of rocks with smaller diameters, while the top layer consist of rocks with larger diameters. In a similar way, other materials may be used to serve as a scour protection, such as for example bricks of prefabricated concrete [10].

Another design that can be used as a scour protection for offshore wind farms is piled up geotextile sand containers [17]. This score protection design includes untreated, mechanically bond nonwoven geotextile that is shaped as a container and filled with sand. The containers can be distributed randomly on the sea bottom, in different layers. The geotextile scour protection can be installed before the foundation of the turbine. [17]. The piles in the foundation of the wind turbine can later be piled through the sand containers. This can be seen as an advantage, since the foundation of the wind turbine is protected directly from when it is installed, and there is no delay. Recent studies have shown that using a scour protection made of geotextile sand containers imply clear advantages when it comes to reducing environmental the impact of the material of a scour protection [17].

2.4 Environmental impact of offshore wind power

Wind power is known to be one of the cleanest and most environmentally beneficial sources of energy [5]. The environmental impact from wind power is low in the operational phases, and in most cases local. However, the low interest for offshore wind power can be due to the association with higher costs and larger logistical issues [2]. It can also have conflicts of interests with different human activities and nature values. Establishing offshore wind turbines in the ocean can affect the marine environment, for example, in ecosystem changes because of an altered movement of sediment in the area [1].

Consequently, the expansion of the offshore wind power industry brings important questions about how the marine wildlife may be affected [2]. Together with the needs to mitigate climate change, it has been clear that the threat against biodiversity is an important question for the future when developing new wind farms [2]. Recent assessments of international oceans show that there are needs to enhance the protection of the marine biodiversity and minimise the total negative impact on the marine ecosystems [2]. These needs are not only considered important in terms of natural conservation, but also in order to ensure the availability of ecosystem services and commodities from the oceans.

2.4.1 Underwater noise and impact on fish

When offshore wind turbines are running and producing electricity, low frequency underwater noise is generated [13]. The noise a wind turbine emits during its operational phase has been estimated to vary between 30 Hz and 120 Hz, where most energy is concentrated between 50 Hz and 80 Hz [12]. The sound level during the operational phase of a wind turbine has through previous studies been measured to be between 87 and 137 dB re 1 micro pascal, with a distance of maximum 100 meters from the wind turbine [13].

An important aspect when establishing new offshore wind power is to understand how the noise generated can affect the marine wildlife [18]. However, in general, noise from for example, ferry traffic often exceeds the sound levels that a wind turbine reaches under its operational phase [13]. The noise level at the wind turbine, the sound source is estimated to be at least 10-20 dB re 1 micro pascal lower than noise deriving from ferry traffic, within the same frequency range [13]. The risk of fish behaviour being disturbed by underwater noise during the operational phase of a wind turbine can by that, be seen as relatively low.

Fish generally have a developed ability to hear [8]. This ability can differ between different species, and the way the sound spreads is affected by the conditions of the water and the character of the sea bottom. Sound waves in water consist of a component of sound pressure and a component of particle motion [19]. While mammals hear sound by detecting sound pressure, fish and invertebrates usually feel sound by particle motion.

3

Methods

The process for the development of this project is thoroughly explained in this chapter. The process involved several stages, including an extensive data collection, the design of the experiments and the procedure for its performance, and the posterior analysis of measurements.

In order to address the raised research questions, three different experiments were proposed and carried out. Nonetheless, the first experiment constitutes the main objective of the present thesis and it is the principal focus of study.

1. An experiment regarding the combined effects of the three suggested scour protections and underwater noise. The behaviour of different fish species were studied in an environment with a scour protection and noise emulating a wind turbine.
2. An experiment to compare the three scour protections based on the fishes preferences.
3. A small-scale experiment with generated currents to understand the scour produced under strong currents conditions around the foundations of an offshore wind turbine.

3.1 Data collection

The data for the project has been mostly taken from relevant publications, but also from some documents and insights from Svea Vind Offshore.

3.1.1 Offshore wind power projects

Previous to the development of the project, it was necessary to understand the characteristics and scope of current of future offshore wind farms projects. Understanding the specific projects Svea Vind Offshore is developing gives an insight on the characteristics of the wind farms: what are the expected positive and negative effects, where they are located, or what are the animal species affected by the construction and operation, among others. This information has been mostly made available by the own company. Other publications regarding operating wind farms, new projects, and their technical characteristics have been consulted. It is relevant to utterly understand the operation and parts of a wind farm.

3.1.2 Study species

The geographical location of a project can give information to identify the specific biota that will be affected by it. Therefore, the study must refer to the local wildlife in the area of influence of the project. Given the fact that Svea Vind Offshore is focusing their projects on Sweden's East Coast [11], and the experiments are carried out on the West Coast, the fish species have to be representative from the Baltic Sea, but they should be present in the Atlantic Ocean (Skarregak) to be fished. The Swedish Agency for Marine and Water Management (Havs- och vattenmyndigheten) [20] served as source to identify fish species that fulfill this requirement. Advice from the local fish provider to Kristineberg Center was considered to determine the species that can be obtained during the time of the experiment. Furthermore, Svea Vind Offshore's preferences were considered.

According to these sources, and evaluating the the validity of different fish species for the study, as well as their availability during the time the experiment was carried out, three species were of interest: Atlantic cod *(Gadus morhua)*, shorthorn sculpin (*Myoxocephalus scorpius*) and black goby (*Gobius niger*). These three fish species were included in the performed experiments.

The Baltic Sea has a rich marine wildlife, with numerous fish species [21]. At temperate and polar latitudes, some species use certain strategies in order to save energy and deal with the cold winters [22]. The fish behaviour can during this period of time be characterized by lower body temperatures, low metabolic rates, fasting and inactivity. This energy-saving strategy was also considered in the study.

3.1.2.1 Characteristics and relevance of the fish species

The selection of the fish is adequate for the purpose of the study, since their natural habitats are relevant for the areas the wind farm projects are proposed within the Baltic Sea. Atlantic cod, shorthorn sculpin, and black goby are found in almost all Sweden's seas [23] [24] [25]. Particularly in the Baltic Sea, cods live in deep-water, mainly because of the salinity [23]. The species is normally found anywhere from the shoreline up until 10-200 meters of depth [26].

The Atlantic cod (*Gadus morhua*) is one of the common fish species that live in the Baltic sea [26]. The fish normally dwells close to the sea bottom, and sometimes also in the free water column. The Atlantic cod is a predator that prey on both fish and invertebrates. Larger individuals of the Atlantic cod can also eat smaller individuals within the same species. Atlantic cod is a highly important species to include in the study, due to its ecological and commercial relevance in Swedish waters. It is of high commercial importance in the North Atlantic region, where it has suffered the consequences from overfishing [27]. Atlantic cod population in the Northeast Atlantic and Baltic Sea has significantly decreased. The risk of its population collapsing has been suggested, making Atlantic cod an especially vulnerable species [27]. Therefore, its inclusion in the experiments allows the study of its vulnerability to offshore wind power farms.

Another common fish species in the Baltic sea, that was included in the study is the shorthorn scuplin (*Myoxocephalus scorpius*) [28]. Shorthorn sculpins live in shallow bottoms [24]. The shorthorn sculpin is a bottom dwelling species that normally can be found from the shoreline to a depth of 60-200 meters. The species are also generally characterized by inactive behaviour [29]. Shorthorn sculpin's high presence in the Baltic Sea [24] makes it relevant to study in the experiments.

Finally, black gobies have been found in most areas of the Swedish Baltic Sea [25]. The black goby lives close to the shoreline, but can also be find on a depth up until 75 meters [30]. The gobies are in most cases bottom dwelling, and to be found among reef structures in the seas [30]. They prefer sandy bottoms with vegetation or rocks [25], and they naturally spend their time in shelters like rocks or shells [31]. In addition, black gobies have been largely recorded on the seabed around offshore wind turbine foundations [32], which enhances its relevance to include in the study.

The studied cods and sculpins can be classified between size: small and medium-sized specimens. Table 3.1 shows the average sizes of the fish specimens used.

Table 3.1: Average size of the fish used in the tests, expressed with the standard deviation.

Fish	**Length (cm)**
Small A. cod	15 ± 3
Medium-sized A. cod	25 ± 5
Small s. sculpin	16 ± 2
Medium-sized s. sculpin	17 ± 5
Black goby	8 ± 2

3.1.3 Scour protections

The selection of the scour protections to be tested has been made based on current projects and published information. It was relevant not only to select a material, but also a configuration for its placing. The analysis of scour protections currently in use, how they are built, and what characteristics they have, allowed the selection of three scour protections:

1. A scour protection made of rocks of small to medium-sized rocks.
2. A scour protection made of concrete bricks.
3. A scour protection made of geotextile sand containers (GTSC).

3.1.4 Underwater noise

Different articles were reviewed to understand the characteristics of the noise that should be played during the experiments so that it is close to reality. Different measurements and information regarding underwater noise from wind turbines operation can be found throughout literature [33] [34]. Furthermore, Svea Vind Offshore has provided data indicating that the radiated noise is dominated by frequencies in the 80 Hz band. Finally, the website Discovery of the sound in the sea [35], developed by the University of Rhode Island, constitutes a renowned source of noise files and information that provided the noise file used in the experiments.

3.1.5 Ethical training

For the experiments to follow the ethical legislation regarding handling with animals, the course given my the Swedish Agricultural University (SLU), named *Swedish legislation and ethics, animal welfare and 3R* was taken previous to the start of any experiment.

Similarly, the course *Fish as research animals*, given by SLU, given the absence of previous qualifications for working with fish was attended. The course included education regarding several aspects involved in the experiments, such as carrying out procedures on animals, such as methods of euthanasia (Function D; 2010/63/EU) or other procedures (Function A; 2010/63/EU), as well as education regarding care taking (Function C; 2010/63/EU) [14].

3.2 Experiments with underwater noise

The experiment designed for this thesis project was to study reactions of different species of fish to a novel environment. It was thus studied their behaviour in relation to underwater noise deriving from wind turbines. More specifically, it was studied the preference of scour protection choice and if this differed between scour material and species. The fish could move from the tank with the scour protection and high noise to a second tank with lower noise, but no scour protection. Having these two tanks with different noise conditions allowed the study of fish preferences: do they prefer to stay close to a scour protection under noisy conditions, or do they prefer to avoid the loud noise and stay in an environment without scour protection but lower noise?

In this section, all aspects regarding this experiment will be presented. The necessary material will be explained, along with the experiment setup that allows the previously described environment. In addition, the fish species that have been used are pointed. Finally, the methodology for carrying out the experiment is described.

3.2.1 Material

The material that has been used can be classified in four categories:

1. Material to create the tanks environment.
2. Equipment to adjust and reproduce the noise.
3. Scour protections.

4. Recording equipment. Two GoPro Hero 12 have been used.

3.2.1.1 Elements to create the environment

Regarding the environment, two tanks have been used. One is meant to hold the scour protection and the noise source. The other tank is meant to recreate a less noisy but emptier environment. The dimensions of the tanks are presented in Table 3.2, having both tanks the same dimensions. Additionally, to recreate a more natural environment, the bottom of both tanks was fully covered with sand taken from Fiskebäckskil (Sweden) coastline.

Table 3.2: Dimensions of the tanks.

Length (cm)	**Width (cm)**	**Height (cm)**
150	100	80

3.2.1.2 Equipment related to the noise

The noise was played using an underwater speaker, which was placed within the scour protection, since that is the noise source in actual wind turbines. The noise file used corresponds to an underwater recording of the sound produced by a wind turbine in the Danish wind farm of Vindeby [35].

To recreate an accurate environment, the noise must be played in the adequate frequency and intensity, which are shown in Table 3.3. Therefore, a calibrated hydrophone (HTI-96-MIN with pre-amplifier, High Tech Inc., Gulfport MS; sensitivity -165 dB re 1 V/μPa, frequency range 0.02-30 kHz) connected to a digital audio recorder (Song Meter SM2+, Wildlife Acoustics Inc., Maynard, US, sampling frequency 24 kHz) was used to record the sound and select the configuration levels of the speaker that provided the desired intensity. Figure 3.1 shows the difference between noise treatment and silent treatment of the fish. A difference of approximately 30 dB was observed between the two different treatments.

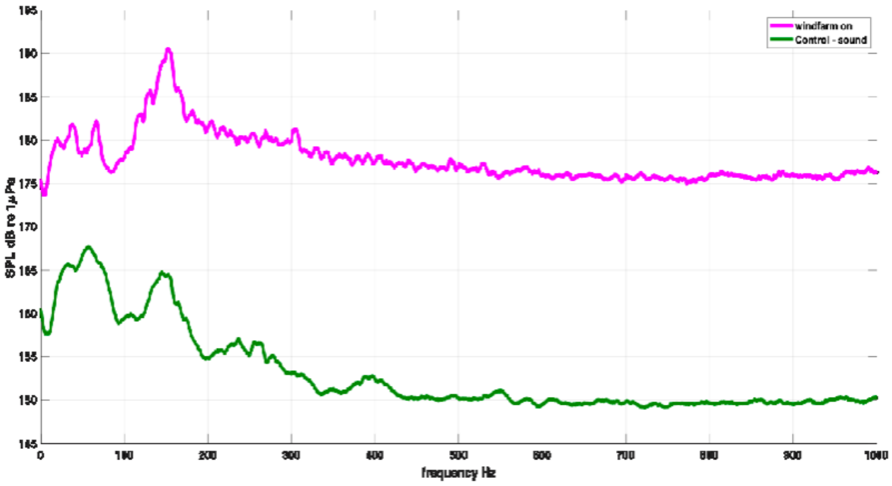

Figure 3.1: Assessment of noise output in the tank. Power spectra for noise and control treatment (silent treatment) shown for 0-1 kHz measured inside the tank. Sound pressure level (SPL) was on average 30 dB higher for noise than for control in this frequency range.

Table 3.3: Frequency and intensity of the sound.

Parameter	Value
Frequency (Hz)	80
Intensity (dB)	137

3.2.1.3 Rocks scour protection used

The rocks that have been used are found in three sizes, which are presented in Table 3.4. They are of granitic nature and have been taken from the surroundings of Fiskebäckskil (Sweden), which contributes to the accuracy in recreating a natural environment.

Table 3.4: Average sizes of the rocks used for the scour protections, expressed with the standard deviation.

Size	Length (cm)	Width (cm)	Thickness (cm)
Small	3 ± 1	3 ± 1	3 ± 1
Medium	13 ± 3	10 ± 2	6 ± 3
Big	25 ± 4	20 ± 4	16 ± 3

3.2.1.4 Geotextile scour protection used

The geotextile sand containers have been constructed in an uniform size, which is shown in Table 3.5. The geotextile used has been a commercial approximation to the actually used in engineering projects. It corresponds with a DuPont Typar®

SF by Byqqros. According to BG Byggros AB, it aligns with many of the desired characteristics for the geotextile: it is non-woven, non-absorbent, it ensures a good filtration, it is highly water permeable and highly resistant [36]. Figure 3.2 shows the constructed scour protection.

Table 3.5: Dimensions of the constructed geotextile sand containers.

Length (cm)	Width (cm)	Thickness (cm)
25	20	7

Figure 3.2: Picture of the GTSC scour protection. The underwater speaker can be seen above the scour protection.

3.2.1.5 Concrete scour protection used

Concrete bricks have been used to build the scour protection. The dimensions of the bricks is collected in Table 3.6. Figure 3.3 shows the result of the piled concrete bricks.

Table 3.6: Dimensions of the bricks used.

Length (cm)	Width (cm)	Thickness (cm)
20	13	4

Figure 3.3: Picture of the concrete bricks scour protection. A shorthorn sculpin can be seen laying on the left of the scour protection. The underwater speaker (blue) can be seen above the scour protection.

3.2.2 Experiments setup

The setup consisted of the two aforementioned tanks interconnected with four tubes in their long side. Figure 3.4 shows the actual setup in the laboratory. The dimensions and position of these tubes can be seen in Table 3.7. Two tubes were placed closer to the bottom of the tank, meanwhile the other two were placed in the higher half of the tank. This facilitates the transit of the fishes, since shorthorn sculpins are known for being bottom-dwelling fish [37], while Atlantic cods can also move closer to the surface [38].

Figure 3.4: Picture of the experimental setup in the laboratory.

Table 3.7: Position of the connections in the tanks.

	Bottom tubes	Top tubes
Vertical distance from the tanks' bottom (m)	0.060	0.50
Horizontal distance between connections (m)	1.0	1.0

The bottom of the tanks was covered with sand and filled with surface seawater, which was constantly running in the tanks. Both tanks had their water inlet and outlet symmetrically positioned, and had an equal flow. This avoids differences in the tanks that may interfere with the fishes behaviour. The top of the tanks was covered with a camouflage net. This had a double purpose: to avoid fish from eventually jumping out of the tanks, and to create a darker environment.

The scour protection which was tried during the test was set in one of the tanks, on the side against to the tubes and furthest away from the second tank. The underwater speaker was set within the scour protection, next to the tank wall, and must be placed completely under the water level.

To facilitate the comprehension of the results and the analysis of the experiments, the whole setup has been divided into five zones of study. The zones are numbered from 1 to 5, the number one corresponding to the closest to the scour protection and the 5 to the furthest away from it. Table 3.8 introduces the zones, which are graphically shown in Figure 3.5.

Table 3.8: Tanks zones of study.

Zone number	Description	Tank
1	Scour protection	A
2	Next to the scour protection	A
3	Connections in between the tanks	-
4	Empty tank, closest to the tubes	B
5	Empty tank, furthest from the tubes	B

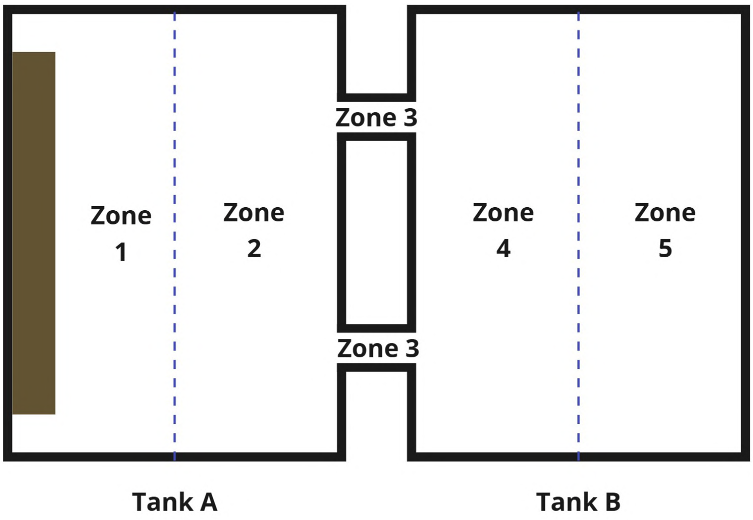

Figure 3.5: Overview of the zones in the tanks setup. Zone 1 represents where the scour protection is set, while Zone 3 represents the connections between tanks. The zones number go from 1 to 5 directly showing the distance from the scour protection.

3.2.3 Experiments performance

A series of three experiments with the same methodology has been carried out. Each one of the three experiments corresponded with the study of one of the three proposed scour protections: rocks, geotextile sand containers, and concrete bricks. Within each experiment, a total of four tests. A test consisted of three phases and lasted for 3 hours. The phases it comprised are:

1. Acclimation. A fish of each species was set in a big cage inside the tanks for 1 hour. The cage is set in zone 2.
2. Environment without noise (ambient treatment). The fishes were freed and left in the tanks setup for 1 hour.
3. Environment with noise (noise treatment). The noise from the wind turbine started playing, so that the initial reaction of the fishes and their behaviour during the next hour can be observed.

The acclimation time helped the fishes feeling comfortable in the new environment they had been put into. The duration of this phase was 1 hour, which was based on other similar studies [38] and on the experience, which showed that this was a reasonable time for the fishes to acclimate to the new conditions. As mentioned, the initial point for the fishes is zone 2. The reasoning behind this is that the fish can explore both the scour protection and the connections between tanks when they are freed. Table 3.9 shows an overview of the whole tests process.

Table 3.9: Tests process overview.

Number	Phase	Noise	Duration
1	Acclimation	No	1 h
2	Ambient treatment	No	1 h
3	Noise treatment	Yes	1 h

Carrying out the observation of the species under both noisy and non-noisy conditions allowed the comparison between the two experiments for the same species individuals. Furthermore, it provided information about the initial reaction of the fishes when the noise starts playing.

The whole experiment except the acclimation was documented with pictures. Photographs were taken for 2 hours with an interval of 1 minute. This recording time is higher than the carried out in similar experiments [38], giving a larger amount of data. Two cameras were in use, one on each tank, allowing the complete observation of the setup. This provided a total of 240 photographs for each test. Figures 3.6 and 3.7 show how the pictures taken look like in the tank with scour protection (Tank A) and the empty tank (Tank B).

Figure 3.6: Picture of Tank A with the concrete bricks scour protection. An Atlantic cod can be observed swimming around the scour protection.

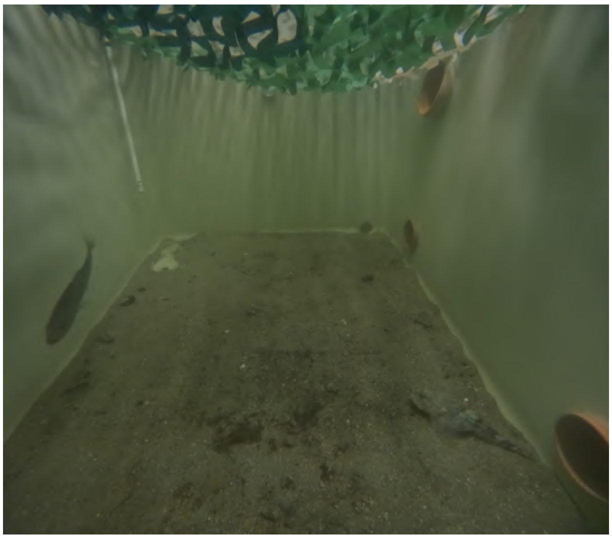

Figure 3.7: Picture of Tank B. An Atlantic cod and a shorthorn sculpin can be observed.

3.2.4 Data registration

Data for this experiment was obtained through the analysis of photographs taken during each test. For each test, high-resolution images were captured at predetermined intervals to ensure comprehensive coverage of fish distribution across the zones. These images were subsequently analysed to accurately determine the position of each fish at various time points. The procedure for registering the data involved several steps:

1. Image capture. Photographs were taken using a high-resolution camera mounted strategically to cover the maximum experimental area.
2. Image analysis and position registration. Each image was examined individually to identify and locate each fish. The position of each fish was mapped onto a grid corresponding to the defined zones of the experiment.
3. Position registration. For each fish identified in the image, its position was recorded according to these zones.
4. Data compilation. The occurrences of each species in the respective zones were compiled for each test. This compilation allowed for the calculation of the frequency with which each species was observed in each zone throughout the duration of the experiment. Fish that was not visible in the recordings (because of hiding between the cameras or the scour protection) were not counted into the data, hence some observations went missing during the experiment. If there was enough evidence that a fish was within the scour protection, but still not visible in the recordings, it was assumed that it was present in zone 1. This happened when there were pictures of the fish entering the scour protection and getting out of it.

3.3 Experiment to compare the scour protections

This experiment is based on the previous one, but its main goal was to observe if during the tests the species of fish used have a preference when being freed in an environment where two scour protections are present. These experiments were carried out without noise. Thus, it is only based on the physical characteristics of the scour protections.

The material used was the same one as for the previous experiments, excluding the equipment to play the noise. Regarding the fish species, only Atlantic cod and shorthorn sculpin were tested, avoiding black gobies because of their observed inactive nature. The setup is similar, with the characteristic that each tanks had a scour protection. There was therefore no empty tank. The zones were divided as shown in Table 3.10.

Table 3.10: Tanks zones of study for the scour protection comparison experiment.

Zone number	Description	Tank
1	Scour protection 1	A
2	Next to the scour protection 1	A
3	Connections in between the tanks	-
4	Next to the scour protection 2	B
5	Scour protection 2	B

3.3.0.1 Experiment performance

Given the existence of two scour protections to test, the procedure to carry out the experiment slightly differs. Three tests of 2 hours each were performed according to Table 3.11, allowing all three scour protections to be tested against each other. Each experiment had two phases:

1. Acclimation. A fish of each species was set in two big cages inside each tank for 1 hour. The cages were set in zone 2 and 4.
2. The fish were freed and left in the tanks setup for 1 hour.

In contrast to the previous experiments, a total of four fish individuals were present in the tanks, two from each species. Since one of each species started in each tank, it was easier to observe if they have a preference for any of the two scour protection. Data registration was carried out as in the underwater noise experiment, as explained in Section 3.2.4.

Table 3.11: Three different tests to compare the scour protections.

Test	Scour protection 1	Scour protection 2
1	Concrete bricks	Geotextile sand containers
2	Rocks	Geotextile sand containers
3	Rocks	Concrete bricks

3.4 Experiment with currents

The goal of this last experiment was the study of scouring taking place around the foundations of a wind turbine, which supports the need for an effective scour protection. The experiment was carried out in a hydraulic flume machine in the Seagrass Ecology Lab, at Kristineberg Center (Lysekil, Sweden) [39].

3.4.1 Material

The main equipment used in the experiment was, as mentioned, the hydraulic flume, which can be seen in Figure 3.8. The flume has the capability to generate both currents are waves. Its dimensions are shown in Table 3.12.

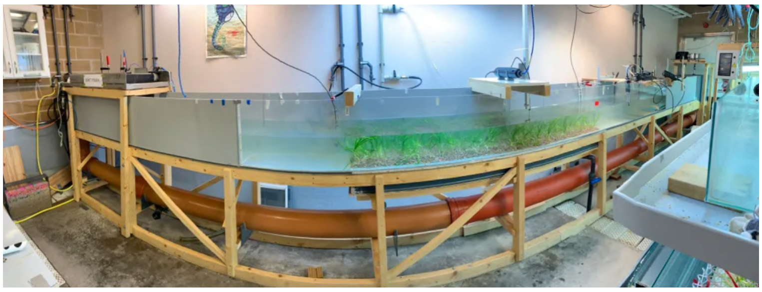

Figure 3.8: Hydraulic flume used for the currents experiments. Picture courtesy of Eduardo Infantes [39].

Table 3.12: Dimensions of the hydraulic flume machine [39].

Parameter	Value (m)
Length	8.0
Width	0.5
Height	0.4
Test box length	2.0

In the hydraulic tube, a vertical tube representing a wind turbine was set, together with smaller scale scour protection. Rocks were tried as scour protection was tried in this experiment, since it is widely used configuration in actual offshore wind farms and it serves the aim of the experiment of observing the dynamics and effects of scouring. Additionally, the purpose of the experiment was to observe the scouring reduction when having a scour protection. The dimensions of the scour protection are presented in Table 3.13, while the tube's external diameter was 5.1 cm.

Table 3.13: Dimensions of the rocks used in the rock scour protection tested in the hydraulic flume machine.

Length (cm)	Width (cm)	Thickness (cm)
3 ± 0.5	3 ± 0.5	3 ± 0.5

Finally, two GoPro Hero 12 have been used to document the currents study.

3.4.2 Performance of the currents experiment

First, the tube was vertically set up in the test box inside the flume. The experiment is divided in two tests:

1. Test without scour protection.
2. Test with rocks scour protection.

Rocks were used as scour protection in the test because initial observations indicated that it was the preferred design by the fish. Although not yet statistically analysed, the observations showed that fish were more frequently found around the rocks scour protection compared to other designs.

Both tests were run for 15 minutes with current at a speed of approximately 10.1 cm/s. This speed is consistent with the upper bound of the usual speed range for currents in the surface layer of the Baltic Sea [40]. Currents seen in the deeper Baltic Sea are slower [40], therefore the set experimental speed is a good approximation to test. Additionally, a current of 20 cm/s was tried in the test without scour protection, to be able to observe scouring with faster currents. The results were photographed for further analysis.

3.4.2.1 Calibration of the hydraulic flume

The engine generating currents is manually controlled through an inverter. Therefore, it was necessary to calibrate the equipment to determine the corresponding current speeds. A Doppler velocimeter (Nortek Vectrino) was used to measure the current speed at different engine revolutions, which is an non-dimensional unit. Figure 3.9 shows the calibration curve, and Equation 3.1 the curve equation, which has a R^2 value of 0.9944, proving its significant accuracy.

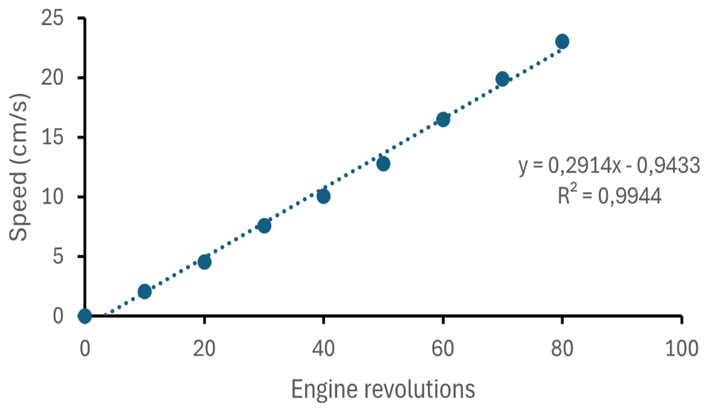

Figure 3.9: Calibration line for the currents speed in the hydraulic flume.

$$v = 0.2914x - 0.9433 \tag{3.1}$$

3.5 Analysis method

After the experiments were carried out and the raw data was set, an analysis was conducted. Firstly, the data was analysed through simpler comparisons of the raw data. This resulted in a brief analysis that could show indications of where the fish preferred to stay and under what conditions. This analysis was afterwards presented in tables and diagrams. A statistical analysis is subsequently conducted.

3.5.1 Statistical analysis

After the brief analysis was conducted, to further analyze the data, a statistical analysis was performed. The statistical analysis was performed in the software SPSS, by IBM. The first step of the analysis was to check if the data from the experiments was normally distributed or not. To determine the normality of the data a Kolmogorov-Smirnov test was carried out [41].

If the Kolmogorov-Smirnov showed that the data was distributed normally, a parametric test, like ANOVA analysis, was conducted [42]. If the Kolmogorov-Smirnov showed that the data was not normally distributed, then a non-parametric test was conducted, a Wilcox signed rank test [43]. The performance of these tests showed if the results from the carried out experiments were significant.

4

Results

This chapter presents the results obtained carrying out the three experiments of the project following the methodology explained in Chapter 3.

4.1 Results of the experiment with underwater noise

The results for Atlantic cod and shorthorn sculpin are presented in the following sections. Regarding the black goby, its observations were notably low, as it was noticed in all replicates to hide inside the scour protection from the early start of each test. Therefore, no significant data from the black gobies observations are shown.

Before analysing the data, it was necessary to determine whether the distribution of the data followed a normal distribution. In order to determine this a Kolmogorov-Smirnov test with the Lilliefors correction was conducted. In summary, the Kolmogorov-Smirnov test with the Lilliefors correction indicates that most of the data follows a non-normal distribution, except for the data in the experiments with Atlantic cod in both the rocks and geotextile sand containers scour protections. This supports the use of a non-parametric statistical tests in subsequent analyses. For the data from the mentioned tests that follow a normal distribution a parametrical analysis was carried out.

To determine whether there was a significant difference between the ambient and the noise treatment among zones, a Wilcoxon Signed Ranks Test was conducted, to compare the median differences between the treatments. This non-parametric test was chosen due to the non-normal distribution of the collected data set. With the data that was normally distributed, the analysis of variance method (ANOVA) was performed. The results are presented below. If the p-value for the tests is lower than 0.05, the results are significant.

4.1.1 Rocks scour protection

In this section, the results for the rocks scour protection are presented for Atlantic cod and shorthorn sculpin, respectively.

4.1.1.1 Atlantic cod

The results showed that there was no significant difference in zone 1 between treatments. The same applies to zones 2, 3, 4 and 5. (ANOVA: Zone 1, F=16.6, p=0.728, n=3; Zone 2, F=112.7, p=0.236, n=3; Zone 3, F=0, p=1, n=3; Zone 4, F=0.041, p=0.850, n=3; Zone 5, F=0.515, p=0.513, n=3) (Figure 4.1). However, cod has been observed in zone 1 more than in zone 5 during both treatments. Figure 4.2 shows an overview of the total observations for the Atlantic cod in the rocks scour protection.

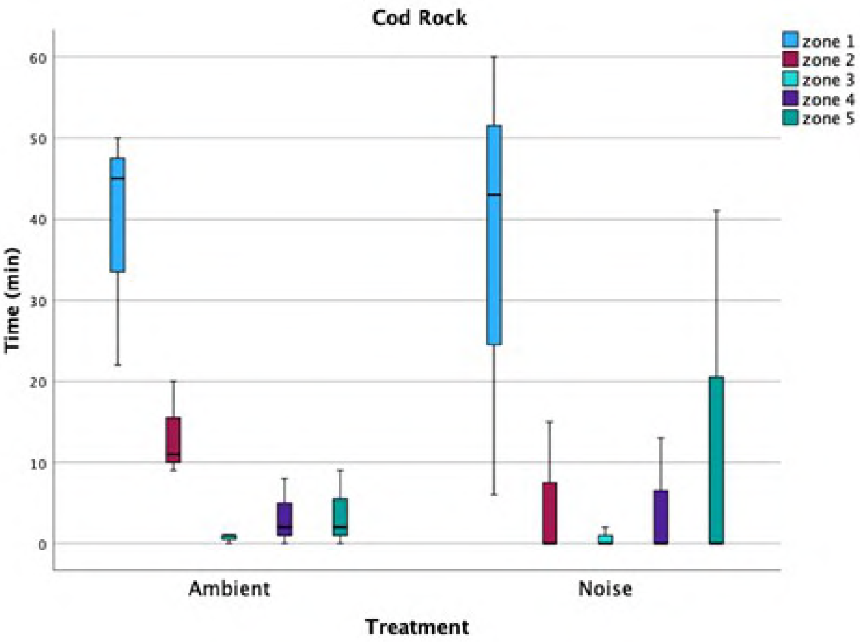

Figure 4.1: Boxplots show the distribution of cod in the rocks scour protection between ambient and noisy treatment. Boxplot show the 25th, 50th (median), and 75th percentiles. Whiskers show the range of the data, with outliers.

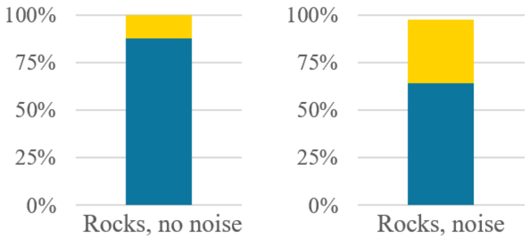

Figure 4.2: Results in percentage of the time the cod spent in different zones when trial with the rocks scour protection. Results are shown as a percentage of the total amount of time. Blue shows sightings in Tank A (scour protection and noise source), and yellow, sightings in Tank B.

4.1.1.2 Shorthorn sculpin

The shorthorn sculpin spent significantly more time in zone 1 when noise treatment was on, compared to the ambient treatment. When there was no noise in the tank, the shorthorn sculpin spent significantly more time in zone 2 compared to the noisy treatment. There was no significant difference between zone 3, zone 4 and zone 5 between treatments. (Wilcoxon Signed Ranks Test: Zone 1, z=-2.201, p=0,028; Zone 2, z=-1.992, p=0,046; Zone 3, z=1.000, p=0.317; Zone 4, z=-0.378, p=0.705; Zone 5, z=-0.378, p=0.705) (Figure 4.3). Figure 4.4 shows an overview of the total observations for the shorthorn sculpin in the rocks scour protection.

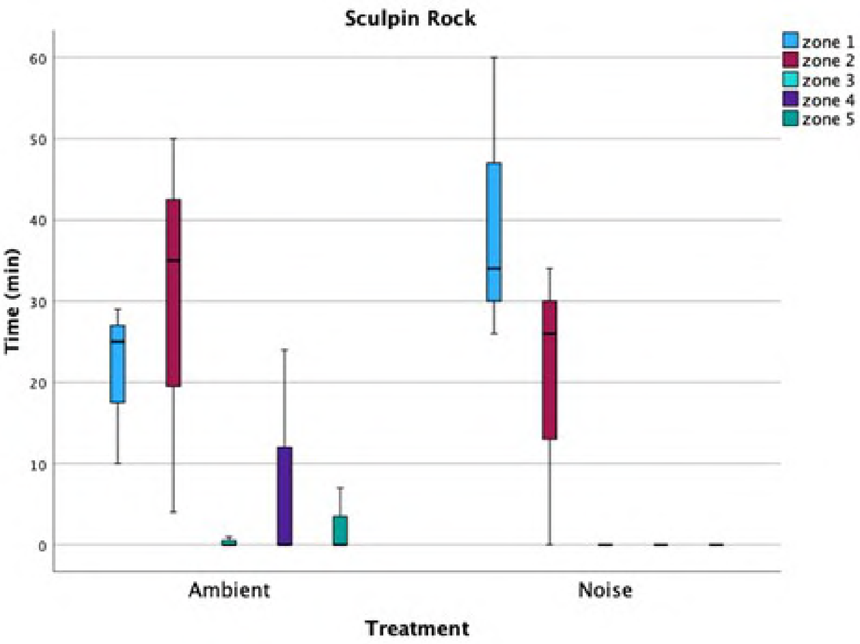

Figure 4.3: Boxplots show the distribution of sculpin in the rocks scour protection between ambient and noisy treatment. Boxplot show the 25th, 50th (median), and 75th percentiles. Whiskers show the range of the data, with outliers.

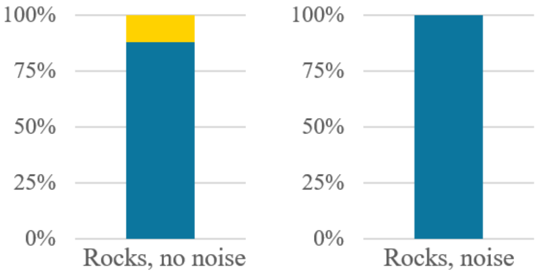

Figure 4.4: Results in percentage of the time the sculpin spent in different zones when trial with the rocks scour protection. Results are shown as a percentage of the total amount of time. Blue shows sightings in Tank A (scour protection and noise source), and yellow, sightings in Tank B.

4.1.2 Concrete bricks scour protection

In this section the results for the concrete bricks scour protection are presented for the Atlantic cod and for the shorthorn sculpin.

4.1.2.1 Atlantic cod

The Atlantic cod spent more time in zone 1 during noise treatment compared to ambient treatment. Zone 1 is the dominant zone, with the higher amount of sightings. Regarding zone 4 and zone 5, the cod spent significantly more time in ambient treatment compared to noise treatment. There was no significant difference between zone 2 and zone 3 between treatments. (Wilcoxon Signed Ranks Test: Zone 1, z=-2.197, p=0,018; Zone 2, z=-1.866, p=0,062; Zone 3, z=-0.378, p=0.705; Zone 4, z=-2.201, p=0.028; Zone 5, z=-2.213, p=0.027) (Figure 4.5). Figure 4.6 shows an overview of the total observations for Atlantic cod in the concrete bricks scour protection.

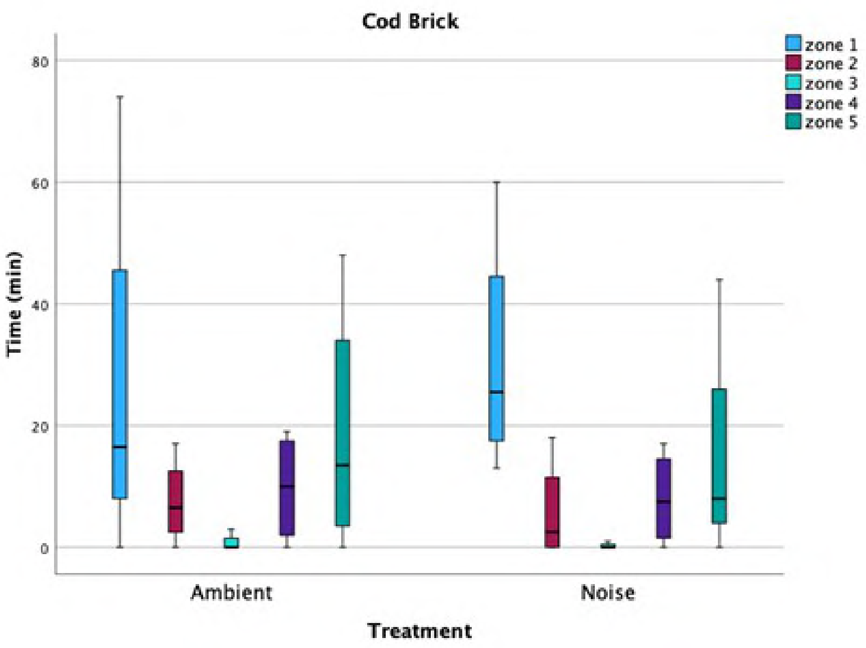

Figure 4.5: Boxplots show the distribution of cod in the concrete bricks scour protection between ambient and noisy treatment. Boxplot show the 25th, 50th (median), and 75th percentiles. Whiskers show the range of the data, with outliers.

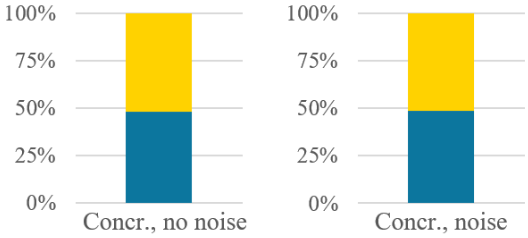

Figure 4.6: Results in percentage of the time the cod spent in different zones when trial with the concrete bricks scour protection. Results are shown as a percentage of the total amount of time. Blue shows sightings in Tank A (scour protection and noise source), and yellow, sightings in Tank B.

4.1.2.2 Shorthorn sculpin

The shorthorn sculpin spent significantly more time in zone 1 during ambient treatment compared to noise treatment. The species also spent significantly less time in zone 2 during noise treatment compared to ambient treatment. There was no significant difference between zone 3, zone 4 and zone 5 between treatments. (Wilcoxon Signed Ranks Test: Zone 1, z=-2.201, p=0,028; Zone 2, z=-1.992, p=0,046; Zone 3, z=-1.000, p=0.317; Zone 4, z=-0.378, p=0.705; Zone 5, z=-0.378, p=0.705) (Figure 4.7). Figure 4.8 shows an overview of the total observations for the sculpin in the concrete bricks scour protection.

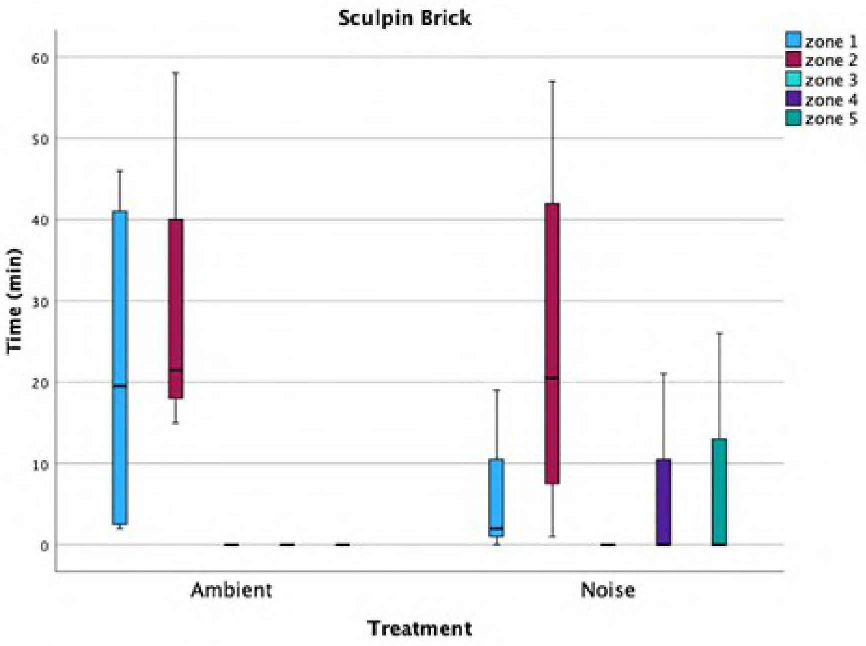

Figure 4.7: Boxplots show the distribution of sculpin in the concrete bricks scour protection between ambient and noisy treatment. Boxplot show the 25th, 50th (median), and 75th percentiles. Whiskers show the range of the data, with outliers.

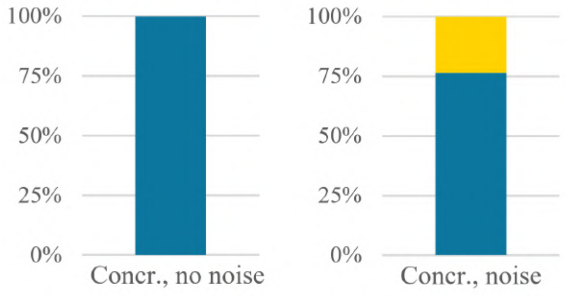

Figure 4.8: Results in percentage of the time shorthorn sculpin spent in different zones when trial with the concrete bricks scour protection. Results are shown as a percentage of the total amount of time. Blue shows sightings in Tank A (scour protection and noise source), and yellow, sightings in Tank B.

4.1.3 Geotextile sand containers scour protection

In this section, the results for the geotextile sand containers scour protection are presented for the Atlantic cod and the shorthorn sculpin.

4.1.3.1 Atlantic cod

The Atlantic cod spent significantly more time in zone 2 during ambient treatment compared to noise treatment. There was no significant difference between zone 1, zone 3, zone 4 and zone 5 between treatments. (ANOVA: Zone 1, F=0.793, p=0.407, n=4; Zone 2, F=7.075, p=0.0308, n=4; Zone 3, F=2.455, p=0.168, n=4; Zone 4, F=0.051, p=0.829, n=4; Zone 5, F=1.827, p=0.225, n=4) (Figure 4.9). During noise treatment the species spent more time in zone 5 than in zone 1. Figure 4.10 shows an overview of the total observations for the Atlantic cod in the geotextile sand containers scour protection.

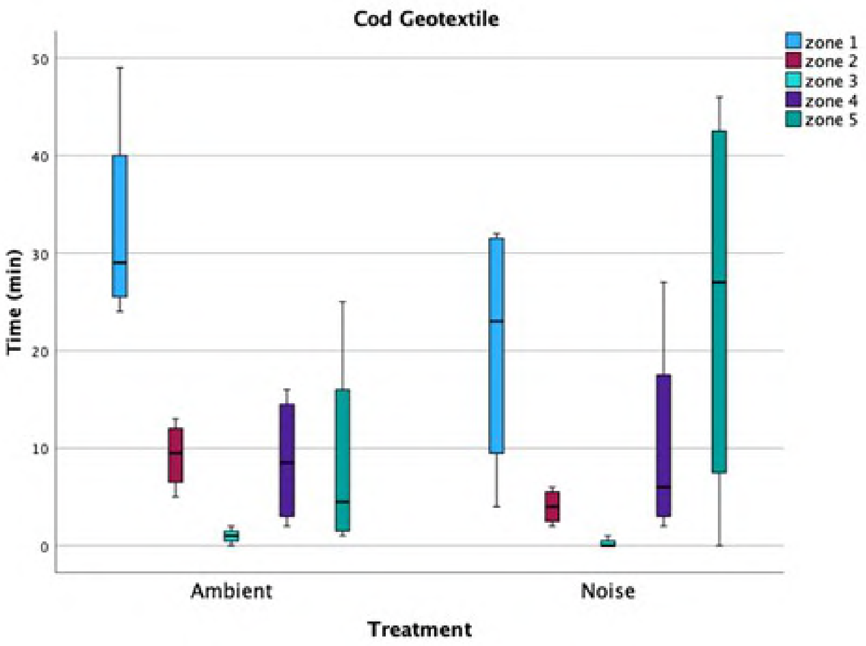

Figure 4.9: Boxplots show the distribution of cod in the geotextile scour protection between ambient and noisy treatment. Boxplot show the 25th, 50th (median), and 75th percentiles. Whiskers show the range of the data, with outliers.

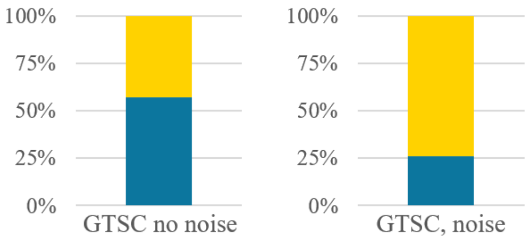

Figure 4.10: Results in percentage of the time the cod spent in different zones when trial with the geotextile sand containers scour protection. Results are shown as a percentage of the total amount of time. Blue shows sightings in Tank A (scour protection and noise source), and yellow, sightings in Tank B.

4.1.3.2 Shorthorn sculpin

The statistical analysis showed that there was no significant effect of noise treatment for the preferred zones in the tanks for the shorthorn sculpin (Wilcoxon Signed Ranks Test: Zone 1, z=-1.863, p=0,063; Zone 2, z=-0.954, p=0,340; Zone 3, z=-1.342, p=0.180; Zone 4, z=-1.577, p=0.115; Zone 5, z=-1.219, p=0.223) (Figure 4.11). Figure 4.12 shows an overview of the total observations for the sculpin in the geotextile sand containers scour protection.

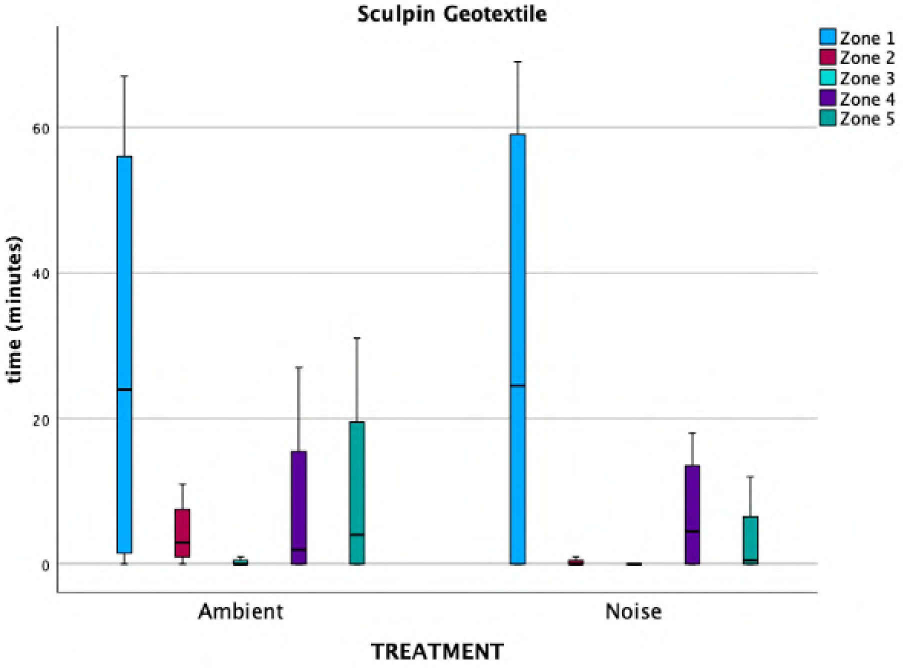

Figure 4.11: Boxplots show the distribution of sculpin in the geotextile scour protection between ambient and noisy treatment. Boxplot show the 25th, 50th (median), and 75th percentiles. Whiskers show the range of the data, with outliers.

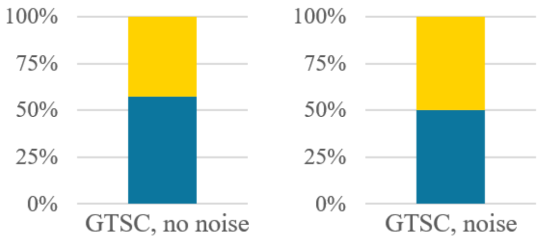

Figure 4.12: Results in percentage of the time the sculpin spent in different zones when trial with the geotextile sand containers scour protection. Results are shown as a percentage of the total amount of time. Blue shows sightings in Tank A (scour protection and noise source), and yellow, sightings in Tank B.

4.2 Results from the comparison between scour protection experiment

Tables 4.1, 4.2 and 4.3 present the results of the experiments with two scour protections and no noise, which were performed with Atlantic cod and shorthorn sculpin. Figures 4.13 and 4.14 plot the distribution of sightings in the tank with each tested scour protection for both species.

Table 4.1: Results from the experiment with concrete bricks and GTSC scour protections. The percentage of sightings in each zone is shown.

	Concrete				**GTSC**
Species	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**	**Zone 5**
A. cod	11.5	34.6	0.0	14.1	39.7
S. sculpin	0.0	93.9	0.0	6.1	0.0

Table 4.2: Results from the experiment with rocks and concrete bricks scour protections. The percentage of sightings in each zone is shown.

	Concrete				**Rocks**
Species	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**	**Zone 5**
A. cod	41.9	14.0	0.0	3.2	40.9
S. sculpin	2.7	5.4	2.7	62.2	27.0

Table 4.3: Results from the experiment with rocks and GTSC scour protections. The percentage of sightings in each zone is shown.

	GTSC				**Rocks**
Species	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**	**Zone 5**
A. cod	23.4	24.7	1.3	13.0	37.7
S. sculpin	4.6	64.4	0.0	2.3	28.7

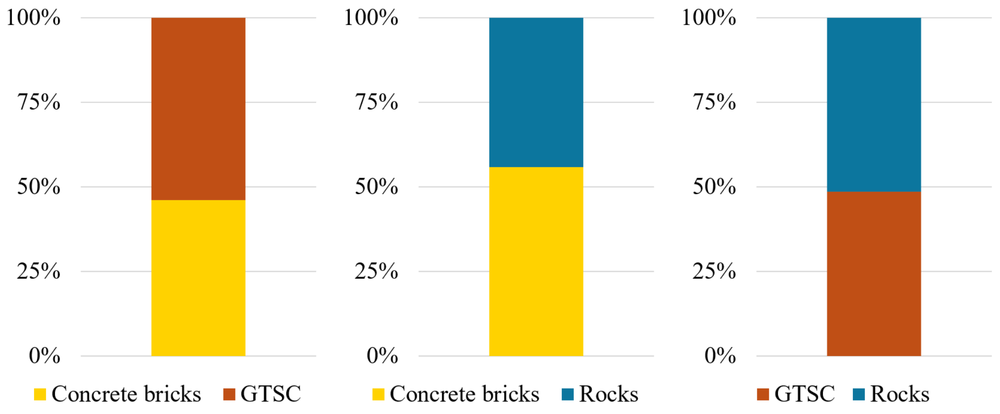

Figure 4.13: Average distribution of Atlantic cod per tanks with different scour protections. Each colour represents the tank where one of the scour protections was placed. Note that each tank has both a scour protection (zones 1 and 5) and sand (zones 2 and 4). (a) Test with concrete bricks and GTSC; (b) test with concrete bricks and rocks; (c) test with GTSC and rocks.

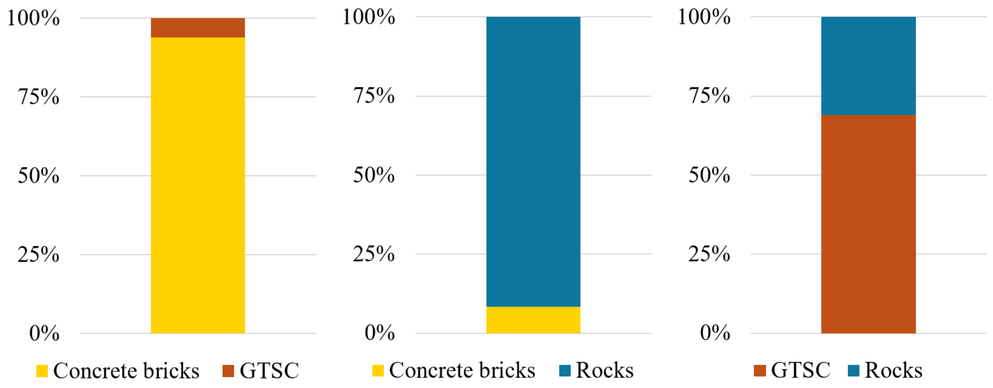

Figure 4.14: Average distribution of shorthorn sculpin per tanks with different scour protections. Each colour represents the tank where one of the scour protections was placed. Note that each tank has both a scour protection (zones 1 and 5) and sand (zones 2 and 4). (a) Test with concrete bricks and GTSC; (b) test with concrete bricks and rocks; (c) test with GTSC and rocks.

4.3 Results from the currents experiment

Two tests were performed to be compared: one without any scour protection and another with rocks scour protection. The results were reported with pictures.

4.3.1 Currents experiment without scour protection

Figure 4.15 shows the initial state of the tower in the flume. As it can be observed, the sandy bottom is completely flat. Figures 4.16, 4.17, 4.18 and 4.19 show the surrounding of the tower after 15 minutes of 10.1 cm/s fast currents from different angles: front, side, back and sand after the tower, respectively.

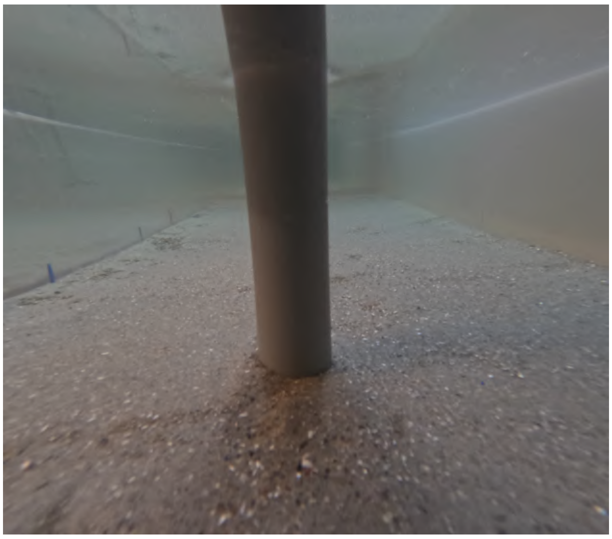

Figure 4.15: Initial state around the tower set in the hydraulic flume.

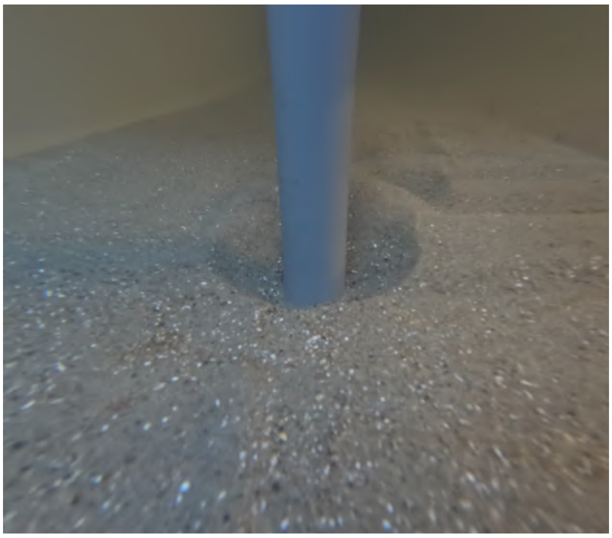

Figure 4.16: View of the surroundings of the tower from the front. The hole made by scouring can be observed.

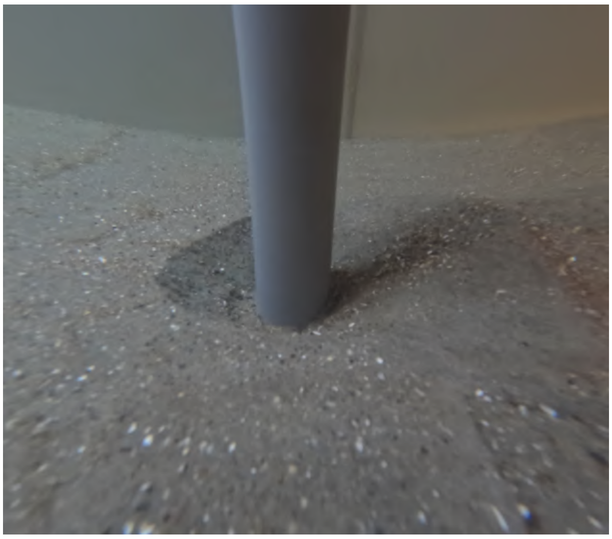

Figure 4.17: View of the surroundings of the tower from one side. The hole made by scouring can be observed.

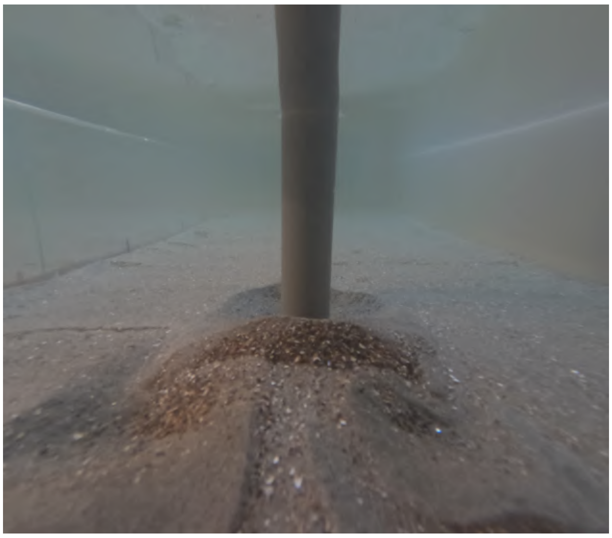

Figure 4.18: View of the back of the tower after exposure to a current.

Figure 4.19: View of the sand basin in the back of the tower after exposure to a current.

4.3.2 Currents experiment with rocks scour protection

Figure 4.20 shows the initial state of the tower in the flume. As it can be observed, the sandy bottom is completely flat. Figures 4.21, 4.22 and 4.23 show the surroundings of the tower after 15 minutes of 10.1 cm/s currents from different angles.

Figure 4.20: Initial state around the tower set in the hydraulic flume.

Figure 4.21: View of the surroundings of the tower from the front.

Figure 4.22: View of the surroundings of the tower from the back.

Figure 4.23: View of the side of the tower from the back.

5

Discussion

In this chapter, the results from the three experiments which were performed are discussed. The limitations that affect these experiments will be considered along the discussion.

5.1 Underwater noise and different scour protection designs

This section discusses the results of the experiments with scour protections for Atlantic cod and shorthorn sculpin, both the experiment with underwater noise and the experiment with two scour protections.

5.1.1 Rocks scour protection

The Atlantic cod showed preference for zone 1 (the scour protection) in both ambient and noisy condition. An interesting observation, even not significant, was that the cod spent less time in zone 2 and more in zone 5 during noise compared to no noise. When noise was off, the cod spent more time in zones 1 and 2. This indicates that the Atlantic cod, which is normally a stationary or slow swimming fish, changed zones at a higher frequency when noise was on. A previous study showed that cod changed the distribution zones and increased swimming speed when exposed to noise [32]. However, when the noise is played, it is observed a movement from zone 2 towards zone 5, but no movement is observed from zone 1. This may suggest that Atlantic cod is disturbed by the noise but appreciates the shelter that the scour protection might provide. Therefore, since there is no protection in zone 2, they move to open water when there is noise. However, they would not move if they are already within the scour protection. This points out that the use of rocks as scour protection may be beneficial for Atlantic cod.

The shorthorn sculpin spent significantly more time in zone 1 under noise exposure, compared to the ambient treatment. Moreover, the sculpin also spent more time in zone 2 during ambient treatment, compared to noise treatment. This suggest that under ambient conditions they might prefer zone 2. There is a movement from zone 2 to zone 1 when the noise is turned on. This is significant and it shows that shorthorn sculpin looks for shelter within the rocks under noise exposure. The sightings in zones 4 and 5 are low, and this preference for staying closer to the scour protection may be due to the fact that rocks resemble to the natural environment that can be found in their natural habitats [24], including a reef structure which provides protection.

The black goby did not show any other preferred zone but in the scour protection, disregarding of the scour protection configuration. This might be due to the cod being a predator on black goby and that the fish therefore sought shelter. Furthermore, gobies naturally spend their time in shelters like rocks or shells, and therefore went for the natural habitat rather than a choice for treatment [31]. Nonetheless, because of their small size and high desire to hide in the scour protection, their sightings were notably low in the cameras. Therefore, from the results, black goby did not present a preference for any of the three scour protections tested. In addition, due to the lack of data from its sightings, no statistical analysis was made.

5.1.2 Concrete bricks scour protection

When testing the concrete bricks scour protection, the Atlantic cod spent significantly more time in zone 1, the scour protection, during noise treatment compared to ambient treatment. There was no significant difference between zone 2 and zone 3 between the treatments. This could mean that the species had a reaction when the noise was turned on, and therefore it was swimming out of the scour protection and further away from the noise. The results point towards zones 4 and 5, which were placed the furthest from the sound source, attracting the Atlantic cod when there was no noise exposure. The Atlantic cod clearly showed a reaction towards the noise and a preference of staying far away from it. The cod changed zones more frequently when noise was on, similar to the case with rocks. This can be explained in line with cod increasing its swimming speed when exposed to noise [32]. The patterns show that the scour protection made of concrete bricks did not attract the species when the noise was turned on as much as the rocks, but it may still indicate the suitability of this scour protection configuration to provide shelter for the species when the environment is stressful.

The shorthorn sculpin spent significantly more time in zone 1 during ambient treatment, compared to noise treatment. The sculpin also spent significantly more time in zone 2 during ambient treatment. The sculpin moves away from zone 1 under noise exposure, and there is a movement to zones 4 and 5 during this treatment. This may indicate that the concrete bricks did not attract the fish when the noise was turned on.

5.1.3 Geotextile sand containers scour protection

The results from the experiment with the geotextile sand containers scour protection show that the Atlantic cod spent significantly more time in zone 2 in the ambient treatment compared to noise treatment. The patterns point towards the cod spending more time in zone 5 when the noise was being played. There is a movement from zone 2 to zone 5 when the noise is turned on. In a similar way, it can be observed that there is not a clear movement from zone 1 when the species is under noise treatment. This may indicate that cod tries to avoid the noise source, because geotextile sand containers did not provide enough shelter for the species. Atlantic cod has shown to prefer the scour protections made of rocks and concrete bricks under the same circumstances.

The shorthorn sculpin showed no significant preference for any of the zones or between the treatments. Even though not statistically significant, the results show that they spent more time in zone 1 under both treatments. The species is only found in zone 2 during the ambient treatment, however not during noise treatment. These results could together indicate that the species moved into the scour protection to seek protection, both during noise and ambient treatment.

5.1.4 Testing the scour protections against each other

When two scour protections were tested against each other the Atlantic cod did not show a particular interest in any material or design. The results were similar for the shorthorn sculpin. This test would have benefited from more replicates, and a further analysis. Replicates with noise would have been relevant given that fish seem to be affected by noise.

An analysis comparing zones 1 and 5 could be argued to give clearer results regarding which scour protection the fish do prefer. However, that would leave behind zones 2 and 4 including numerous observations. Zones 2 and 4 contribute to the environment created in each tank and it was therefore decided to be included in the study.

5.1.5 Fish behaviour with possible effects on the study

It became clear at the beginning of the study that the fishes behave differently depending on the species. The Atlantic cod was found to be the most lively fish, and it was hence willing to discover larger areas of the tanks. On the other hand, there were the black goby and the shorthorn sculpin, which seemed to quickly find a spot to hide in the tank and then stay there for the rest of the experiment time. In many cases this was close to the different scour protections. This can be linked to the fact that it was decided to mix three fish species in the same experiment, which clearly had an effect on each other. For example, the Atlantic cod is, as mentioned in section 3.1.2, a predator on goby and possibly smaller sculpin, therefore the other fish species might have been searching for shelter where they could hide from the cod [26].

5.1.6 The procedure of recording the experiments

Another factor that had an effect on the study was the procedure of recording and setup. The underwater cameras were mounted on one end of each of the tanks and this meant that they could record most of the tanks (around 90 percent), however some angles were left out. This could have had an effect on the results, since fish could have been in these areas and hence not seen in the camera footage and included in the results. This meant that several possible observations were left out of the data because of uncertainty regarding the location of the fish. There are also cases in which the fish hid in or behind the scour protections and therefore it was not possible to localise in the footage. When viewing the camera footage, some assumptions were made. If, based on the recordings, it was clear that the fish was hidden within the scour protection, then it would be assumed that it was in zone 1. This could happen, for example, when observing a fish entering the scour protection and then observing the fish coming out again and then not being seen on the next footage. However, mounting more cameras would definitely have prevented the issue with some of the angles being left out.

5.1.7 The sound source during the experiment

The sound level and sound frequency measured in the experiment were 137 dB re 1 μPa at 80 Hz, as explained in section 3.2.1.2. According to section 2.4.1, the frequencies of the underwater sound emitted from an operating offshore wind farm has its main energy between 30 Hz and 120 Hz and a sound level between 87 dB re 1 μPa and 137 dB re 1 μPa.

5.1.8 The selection of fish

In the experiments, a limited selection of fish species were used. The fishes used were also assumed to act as representative for the marine wildlife in the Baltic Sea. Even if three fundamental species were used, the level of coverage for the marine environment may be questioned, since there are more species than those three living in the water of the Baltic Sea. However, the fish species that were studied in the experiment may have experienced the environment differently. Fish generally have a good hearing ability for frequencies under 1000 Hz, although this can vary between the species [19]. Thus, it can be said that the fishes may have experienced the sound differently.

5.2 Discussion of the experiment with currents

The currents experiment implied testing the scour protection that was most preferred by the fishes, against scouring. The rocks scour protection was tested in a flume machine that simulated waves the same speed as in the Baltic sea. This experiment tested a miniature of a wind turbine foundation together with a scour protection, and also without a scour protection. The tests without scour protection resulted in a hole-like change of the sand around the miniature wind turbine monopile foundation, while the tests with the scour protections resulted in no hole. This makes clear that the scour protection clearly benefits the surrounding sea basin in terms of preventing scouring from currents. This also aligns with what was previously described in section 2.3.

The test with the flume machine came with a few limitations. The machine had the capacity of constructing artificial waves and currents. The currents were be simulated to recreate reality. However it may be discussed that these currents do not act as representative since they were carried in a long tube with a limited area, and without any outside motion. The flume machine was calibrated to achieve currents of a speed close to the ones that takes place in the Baltic Sea. The two speeds that were chosen for the experiments may also not be representative to reality since, there could be weather conditions such as storms might have a significant effect on the motion of waves and currents and hence also particle and sediment movement, see section 2.3 [40].

Assumptions were made regarding the size scales of a real wind turbine compared to the miniature version that was created for the flume machine. For more preciseness in the experiment, measurements of a wind turbine and a real life scour protection could have been taken and scaled down more accurately to the miniature size scour protection that was constructed for the test in the flume machine. The recreated wind turbine foundation for the flume machine also included an assumption of a monopile wind turbine foundation. This may not be representative for all offshore wind turbine foundations, since foundations have different foundation types, as explained in 2.2. In addition, the experiment tested one of the three previously constructed scour protections. For more covering results, miniature versions of all of the three constructed scour protections could have been tested in the flume machine. Furthermore, the scouring was presumed to me measured after each of the two tests with the flume machine were carried out. The measurements were taken with pictures, and comparisons of the conditions before and after were made. For stronger and more accurate results, the measurements could have been taken with more precise methods.

6

Conclusion

This study provides important information for future studies on fish considering underwater noise from wind turbines during operational phase. The results show that fish show different responses to both noise and scour protection and that the responses seem to be species-dependent rather than dependent on the design or material of the scour itself.

The Atlantic cod preferred to stay inside the scour protection close to the noise source when testing rocks and concrete bricks. In the case with geotextile sand containers, the cod seems to move more and further away from the noise. Shorthorn sculpin and black goby preferred to hide in the scour protection near the noise source not dependent on the scour protection design. Based on the results, the rocks scour protection may offer the most preferable environment for the shorthorn sculpin and Atlantic cod. Atlantic cod appears to be more attracted to rocks than to concrete bricks, and less to geotextile sand containers. The species seemed to move away from the noise source unless there was a good shelter option. The results suggest that the positive impacts of rocks and concrete bricks as scour protections might compensate for the negative impacts of the noise. The black goby did not show any clear preference for any of the three scour protections. It can be discussed that this is based on the species' natural hiding behaviour. However, its behaviour was consistent throughout the three experiments with scour protections.

The comparison experiment of the scour protections did not demonstrate a clear preference from any species for one particular scour protection design under ambient conditions. It can be suggested to conduct further studies that include a greater variety of species. Furthermore, the experiment with currents successfully highlighted the importance of scour protections in offshore wind power farms, as they effectively protect the foundations of the turbine against scouring.

Overall, the results of the experiments indicate the potential benefits of a rocks scour protection, especially for the studied species under noise exposure. These findings emphasise the relevance of taking into consideration the characteristics of the natural habitat of the species in the design of offshore wind farm projects, as it combines ecological suitability and technical effectiveness.

6.1 Future work

The procedure followed in this project and its performance can serve as a basis for future research, which may lead to further understanding of the topic. Including more species of fish would increase the knowledge about scour protections and underwater noise from wind turbines. This in turn would be able to support further decision-making processes.

Furthermore, whereas the study focuses on the Baltic Sea environment, the experiments were carried out in laboratory facilities on the Atlantic Ocean coast (Skagerrak). Further studies regarding the Baltic Sea area could be developed on the Baltic coast, which would allow to represent the ecosystem conditions more accurately, and access to different animal species that could be included in the tests. Finally, conducting more replicates of future test would contribute to the strength of the study and its results.

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