# Impact of removing a concrete gas platform on benthic communities in the North Sea

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**Keywords**: Benthic biodiversity, marine growth, fouling, North Sea, artificial reef, gravity based foundation, gas platform.

## Abstract

Artificial structures such as oil and gas platform or wind turbine foundations in the marine environment can have a significant local impact on species diversity and population connectivity. It has been argued that this should be considered in removal decisions for offshore infrastructure. World-wide, high numbers of oil and gas installations will be decommissioned in the coming years. Most will be removed, but some will be left in place or relocated to be used as artificial reefs. In the North Sea leaving in place is prohibited but derogations are allowed for gravity based concrete installations. One of the few Dutch concrete platform foundations is the Halfweg gravity based structure (GBS). Halfweg stopped production in 2016, which was followed by decommissioning and removal of the topside and legs of the structure. Currently, only the GBS remains. The owner Petrogas is evaluating options of removal of the GBS and is considering removal and leave-in-place scenarios. To facilitate this evaluation, a study on the fouling macrofauna community on the structure was performed. Samples were taken by commercial scientific divers and species identified, counted and weighed. The results were compared to similar data from box corer samples from the surrounding seabed within 30 km from the Halfweg GBS and to samples from other oil and gas and wind farm structures and a natural rocky reef.

In total, 65 macrobenthic species were observed in 39 samples from the concrete GBS (52 species), steel legs (32) and surrounding rock dump (44). Simpson diversity index was highest on the rock dump at Halfweg (0.71) but concrete (0.54) as well as steel (0.60) were lower than seabed (0.69). 14 of the species on Halfweg were not found in any of the other investigated substrates. Only 10 species on Halfweg were also observed in the surrounding sandy seabed. 31% of the species found in the Borkum Reef Grounds were also observed on Halfweg. Arthropoda contained the most abundant species on Halfweg, with *Monocorophium acherusicum*, *Jassa herdmani*, *Phtisica marina* and *Stenothoe monoculoides* composing 98% of the abundance on the GBS. Mean ash free dry weight was significantly higher ($p<0.001$) on the Halfweg substrates (204 g AFDW per $m^2$) than on the surrounding seabed (65 g AFDW per $m^2$). Between 94 and 99% of the biomass on Halfweg consisted of the plumose anemone *Metridium senile*. This species was absent from the sandy seabed but common on the other reefs. Non-metric multidimensional scaling showed a strong clustering of the reef samples including Halfweg away from the cluster of sandy seabed samples. PERMANOVA showed this was due to differences in habitat type ($p<0.001$). The total biomass on the concrete GBS was estimated to be 262 kg AFDW, with 20 kg on the steel legs and 2,563 kg on the surrounding rock dump, 2,846 kg AFDW in total. The area of seabed covered by these hard substrates was 3,617 $m^2$. A similar area of seabed without concrete structure and rocks would have contained 232 kg AFDW of macrofauna. The presence of Halfweg therefore increases the local biomass a 12-fold.

The results show that the Halfweg structures significantly increase local biodiversity and biomass. Several of the species observed on Halfweg were not reported from the local seabed or other reefs. Removal of the gravity based foundation will significantly reduce local macrofauna biodiversity. Due to the scattering of rock dump after removal, long term local impact on macrofouling biomass is considered low. Leaving the GBS in place as it is will result in the highest number of species conserved to the area.

# INTRODUCTION

The presence of artificial structures such as oil and gas platform or wind turbine foundations in the marine environment can have a significant local impact on species diversity (Dannheim et al., 2019; Fowler et al., 2018). These *de facto* artificial reefs attract a community of epifouling species (Goddard and Love, 2010; Krone et al., 2013; Picken, 1986), fish (Fujii, 2015; Love et al., 2003; Pradella et al., 2014) and even mammals (Russell et al., 2014). Differences as well as similarities between artificial and natural reefs have been reported (Coolen et al., 2018; Dannheim et al., 2019; Wilhelmsson and Malm, 2008). In general the presence of these installations is considered to increase local biodiversity (Dannheim et al., 2019) and population connectivity (Coolen et al., 2020; Henry et al., 2018; van der Molen et al., 2018). This should be considered when decisions on removal of the infrastructure at the end of its productive life are taken (Fowler et al., 2018).

World-wide, high numbers of oil and gas installations will be decommissioned in the coming years (Fowler et al., 2018). With decommissioning, most structures will be removed from their locations and brought ashore for scrapping or reuse. In some cases, foundations of the structures are left in place (Bull and Love, 2019) or relocated to be used as artificial reefs (Picken et al., 2000). In the North Sea area, the OSPAR decision on the Disposal of Disused Offshore Installations (OSPAR Commission, 1998), dictates that "*The dumping, and the leaving wholly or partly in place, of disused offshore installations within the maritime area is prohibited*". However, derogations of this general prohibition are allowed if the country an installation is present in "*shows that there are significant reasons why an alternative disposal [..] is preferable*". One of the exclusion structures offered by the decision is the foundation of gravity based concrete installations.

In the Netherlands the removal obligation for installations has been embedded in the Mining Act (Kingdom of the Netherlands, 2020) which states that an unused mining installation is to be removed. 160 oil and gas production installations are present at sea in the Netherlands (de Vrees, 2019). Most of these consist of steel jacket structures but a few Dutch installations are constructed using a concrete gravity based foundation. To date, none of these concrete structures have been removed from the Dutch North Sea, and no derogations from the OSPAR decision have been proposed, although in 2016 operator ENGIE proposed to leave two jacket foundations in place an additional 15 years as an experiment (Maslin, 2016). After an intense process of stakeholder involvement and assessments, ENGIE decided to remove the jackets after all.

One of the few Dutch concrete foundations is the Halfweg gravity based structure (GBS). The Halfweg gas production platform was built in 1995 and is operated by Petrogas E&P Netherlands B.V., the Netherlands (henceforth: Petrogas). The platform stopped producing in 2016, which was followed by decommissioning. Although the original intention was to remove the GBS together with the legs and topside, a collision of a gas tanker vessel in 2017 damaged the legs, preventing the lift of the whole structure at once (personal communication Alan Shand, Petrogas). Therefore, the topside and legs have been removed from the GBS in 2019 and the concrete structure remains on the seabed. Currently Petrogas is in the process of evaluating options of removal of the GBS and is considering the following four removal scenarios:

A. Full removal by breaking the GBS in small pieces and removing by polyp crane to dispose on shore, spreading part of the rock dump surrounding the GBS to reduce height above seabed;
B. Remove the rock dump and soil (partly) around the GBS, break the soil suction under the GBS (pump water under the GBS), reinstate the GBS buoyancy system and remove the GBS by lifting (single lift) using the lift points or legs;
C. Remove the rock dump and soil (partly) around the GBS, break the soil suction under the GBS (pump water under the GBS), install multiple chains under the GBS (directional drilling) and remove the GBS by lifting (single lift) using the lifting chains;
D. Leave the GBS and rock dump in place as it currently lies on the seabed.

As part of the decision process, a marine growth inventory was performed to compare the biodiversity and biomass of the macrofauna on the structure and rock dump to the local background of fauna present in the seabed and on a larger scale on other structures. In this comparison the four removal scenarios were combined in two options, as scenarios A, B and C we assumed to result in approximately the same long term end situation:

1. The GBS is fully removed and the surrounding rock dump is scattered partly across the area while the remaining rock dump is untouched (scenarios A, B, C);
2. The GBS is left in place and all rock dump remains untouched (scenario D).

Here the results of the marine growth inventory are presented. Comparisons are made with existing data from previous studies at the sandy seabed surrounding Halfweg, other oil and gas installations, a wind farm and a natural rocky reef. The results show that the Halfweg structures have a significant impact on local biodiversity and strongly increase the local macrofauna biomass. Several of the species observed on Halfweg were not reported in data from the local seabed or other reefs. Removal of the Halfweg gravity based foundation will significantly reduce local macrofauna biodiversity.

# MATERIALS AND METHODS

## Study site

The Halfweg gravity based structure (GBS) is located 26 km offshore from the Dutch coast (52.882$^0$N 4.320$^0$E, WGS84, Figure 1) in a water depth of 25 meters. It is a concrete box-shaped structure of 26*28*6 meters (width*length*height; Figure 2) providing a hard surface area available to macrofauna of approximately 1,376 m$^2$. It is placed on the seabed in a south-east to north west orientation and surrounded by rock dump of different sizes (10-70 cm diameter) in a radius of approximately 15-20 meters from the GBS and a height of up to 6 m, covering a total seabed area of approximately 2,889 m$^2$ with rocks (Figure 3). Since rock dump forms complex structures it was assumed that the hard substrate area available for macrofauna was larger than the area of seabed covered. The rock surface area available for macrofauna was calculated by generating 1,000,000 rocks of random size between 10-70 cm length, width and height, calculating the approximated surface area per rock (Graham et al., 1988), in comparison with the seabed covered by that rock, assuming a vertically projected rectangle shaped area (length*width of each rock). This ratio was averaged to 3.59 m$^2$ rock per m$^2$ seabed and multiplied by the 2,889 m$^2$ of seabed covered. It was assumed that the top layer of rocks was fully available for macrofauna on all sides. Unavailability of the surface on rocks touching each other, additional surface available on rocks below the first layer as well as cover by sand of rocks on the edges of the rock dump area were ignored. The estimated total surface area of rocks available to macrofauna was 10,389 m$^2$. Most hard surface present at Halfweg is composed of concrete and rock dump, with a small steel surface available in the form of the remains of the 1.7 m diameter legs, which are between 2 and 3.5 meters in height above the GBS. The legs are hollow and intrude 6 m in the GBS. Since the legs are open on top, inside steel surface of the legs is also available to macrofauna. As water exchange is limited an oxygen or nutrient deprived layer might form in the deep parts of the legs. Therefore only the surface area of the legs protruding from the GBS was considered to be available for marine growth. Total steel surface available to macrofauna was estimated to be 120 m$^2$. The area of seabed covered by the GBS and rock dump combined is approximately 3,617 m$^2$. The walls of the GBS are almost vertical, with a slightly diagonal inclination. The seabed in the area up to 30 km from the structure is largely composed of sand with patches of coarse substrate, mostly located north of the GBS (EMODnet, 2020).

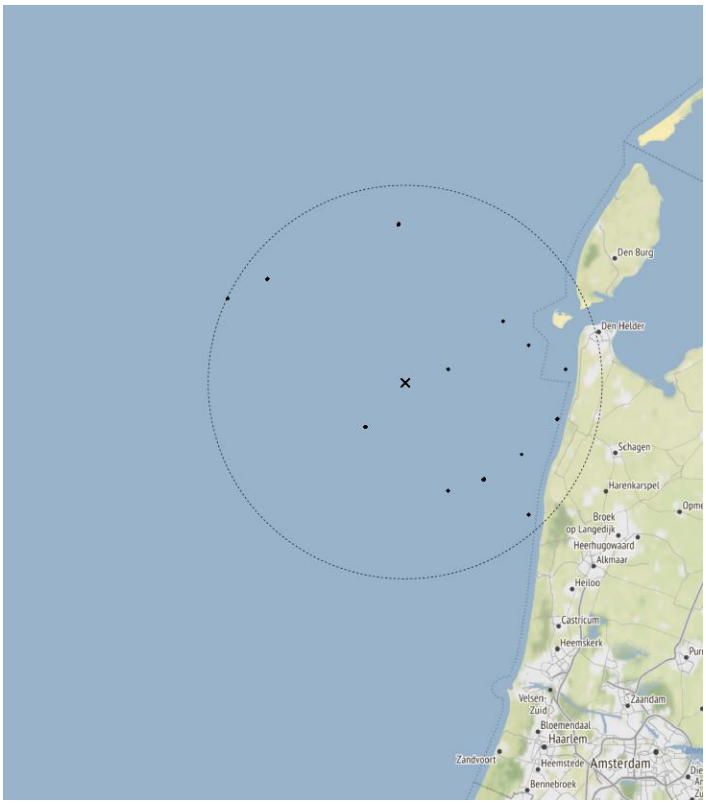


**Figure 1: Sample locations**
Map showing the Dutch coast, position of the Halfweg structure (X) and locations of seabed data extracted from MWTL (black dots) within a 30 km radius from Halfweg (striped line).

**Figure 2: Halfweg gravity based foundation**
Model representation of the concrete GBS as it currently lies on the seabed (rock dump not shown). Provided by Petrogas E&P Netherlands.

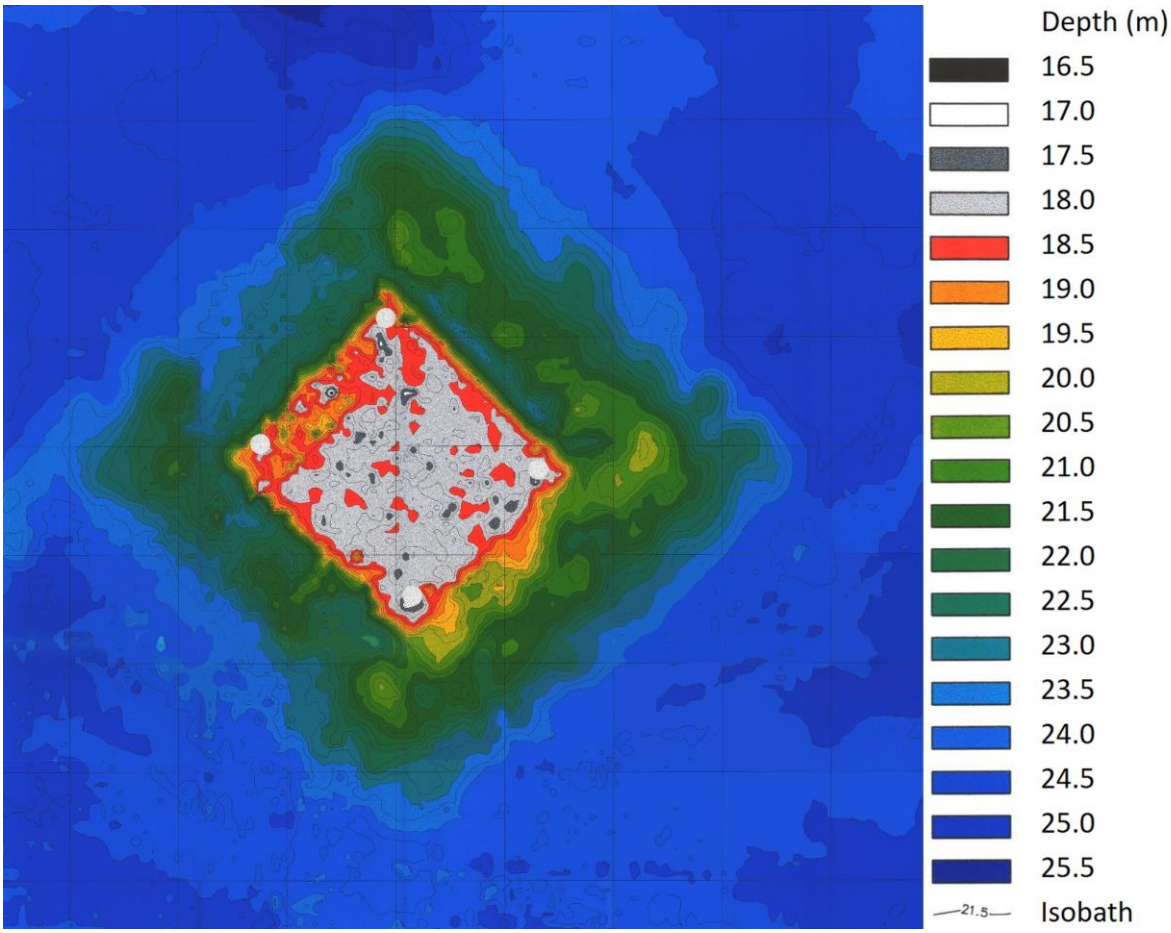


**Figure 3: As-built bathymetry of the Halfweg area**
Bathymetry of the Halfweg gravity based structure (centre square in 45° angle, grey with red area) with surrounding rock dump (green to yellow area) and surrounding seabed (blue area), with legend of depths in m. Lines show 0.25 metre isobaths. Legs shown as white circles. Provided by Petrogas E&P Netherlands.

## Data acquisition

***Sampling of the Halfweg structure***

In September 2019 a survey was conducted to acquire samples from the marine growth present on the gravity based structure (GBS) including the steel legs, as well as from the surrounding rock dump. Samples were taken by commercial diving certified marine biologists using scuba equipment. Samples were collected along transect lines placed in four directions on the GBS (Figure 4). In each direction, two samples were taken from the horizontal top of the GBS, three samples from the vertical-diagonal side of the GBS and three from the rock dump. Finally, seven samples were obtained from the outside vertical surface of two steel legs. In total 39 samples were obtained. Each sample covered 0.05 $m^2$ and was taken from a steel frame measuring 31.6 * 15.8 cm, held in place by one of the two divers in a team. All marine growth within the frame was scraped off using a putty knife and the removed fauna sucked up by an airlift sampler fed by a scuba tank. The airlift sampler was based on a combination of the samplers described in Coolen et al. (Coolen et al., 2018, 2015a). The putty knife was attached to the airlift via a flexible ribbed hose with an inner diameter of 50 mm. This was connected to a 48 mm outer diameter stainless steel pipe to which the air inlet was connected. The flow of air was regulated by a needle valve, which was connected to a scuba tank regulator by a 10 bar pressure hose as is used to connect to inflators of e.g. scuba dive suits. The stainless steel pipe was connected to a straight 50 mm outer diameter pvc pipe ending in a 180° bend on top, made of 75 mm outer diameter pvc. This then fed into a sample net with a mesh size of 0.5 mm. The total length of the airlift above the air inlet was 150 cm. The nets were fixed to the end pipe with a screw connection. This allowed easy exchange of nets during the dive. Between samples, the net was replaced by an empty one and the used net sealed off with a

numbered screw cap. In 50 minutes dive time, a two person dive team was able to collect up to 12 samples.

After collection, the samples were processed on board, by depositing the collected fauna in a sieve with 212 µm mesh size and rinsing the nets with seawater to collect all specimens. Then each sample was drained of water and a volume of ethanol 99% measuring at least twice the volume of fauna was added to each sample. Within 48 hours, the ethanol was drained from each sample and replaced with fresh ethanol 99%, again with a volume of at least twice the volume of the fauna.

All samples were processed in the benthic laboratories of Bureau Waardenburg b.v. and Wageningen Marine Research. Each sample was sorted in taxonomic groups, after which all specimens were identified to the lowest possible taxonomic level, ideally to species level. The World Register of Marine Species (WoRMS Editorial Board, 2019) was used as a reference of taxonomic nomenclature. If more than 200 individuals of the same species were present in a sample, this species was not removed during sorting but left in the sample which was then sub-sampled to a level at which the sub-sample contained between 100 and 200 individuals of the species. After identification, the individuals from each non-colonial species from each sample with a wet weight >0.01 g were ash free dry weighed (6 hours at 500°C after drying) using a Precisa Gravimetrics prepASH 340 series. Colonial species such as Bryozoa, Hydrozoa, Porifera and Tunicata were not weighed or counted, but the size per species per sample was estimated to the nearest $cm^2$.

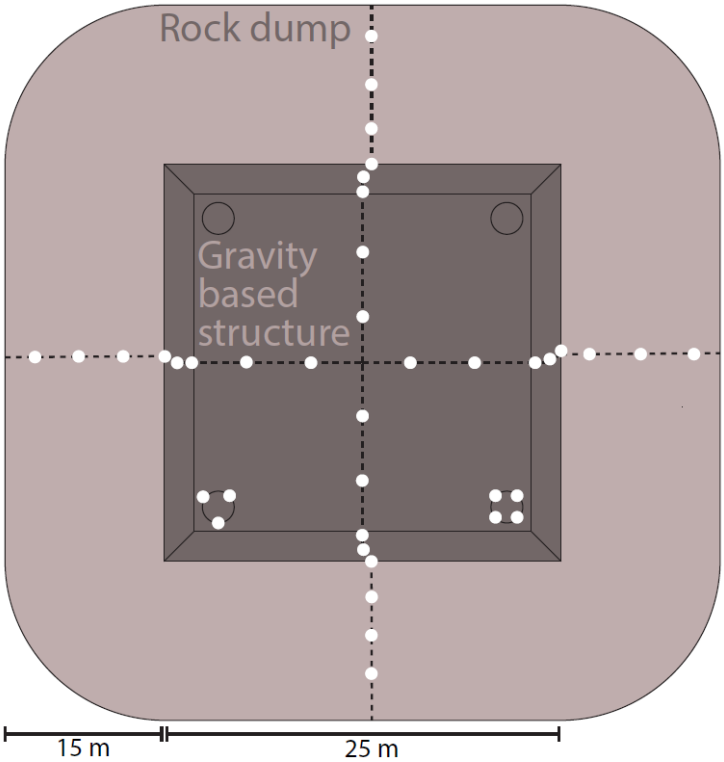


**Figure 4. Sample locations**
Schematics of the sampling design (top view, not to scale). Samples (white dots) were taken in four directions on the gravity based structure (GBS; dark colour), surrounding rock dump (light colour) and on legs (black rings in corners of GBS).

***Seabed data***
To allow a comparison of Halfweg macrofauna with the environmental background, macrofauna data from seabed macrofauna were acquired from the published North Sea macrofauna dataset of the long term measurement programme MWTL (Monitoring Waterstaatkundige Toestand des Lands) in the Netherlands. The MWTL dataset is published with a creative commons zero licence by the Dutch Marine Information and Data Centre (Marine Information and Data Centre, 2019). It covers the whole Dutch part of the North Sea and includes data on macrofauna samples taken using various methods. For

comparison with the airlifted macrofauna samples from Halfweg, only macrofauna data that were within range of 30 km from the Halfweg structure and were sampled using box corer and sieved on a 1 mm mesh (no smaller mesh size was available) were included. The resulting dataset held 2,003 records from 118 samples. These samples had been taken between 1991 and 2015, with yearly samples between 1991 and 2010 as well as samples in 2012 and 2015.

***Artificial & natural reef data***

To assess the uniqueness of the species on Halfweg on a larger scale, a set of published marine growth data from reefs in the Dutch part of the North Sea was used (Coolen et al., 2018). These data contain scraped samples from five oil and gas structures, a wind farm and a rocky natural reef in the Borkum Reef Grounds. The locations are between 32 and 184 km distance from Halfweg. Samples were taken by divers using a similar airlift as used for Halfweg (the platforms, rocky reef) or a sampling net (wind farm). In total, data used was based on 145 samples. The data contained only species abundances (individuals per $m^2$ or presence-only for colonial species) and no biomass data.

***Data preparation***

For data preparation and analysis, R version 3.6.1 (R Core Team, 2019) and Rstudio version 1.2.5001 (RStudio, 2019) were used. Before analysis, all data were updated to include the most recent species names as published on the World Register of Marine Species (WoRMS Editorial Board, 2019), using the *wormsbynames* function from the worms package (Holstein, 2018). For the seabed data, no depth was published, therefore at each sample location, seabed depth was obtained from EMODnet bathymetry data (EMODnet, 2019) using the extract function from the raster package (Hijmans, 2019). This resulted in a mean depth of 22 m from a range of 9 to 33 m. Mean depth of the Halfweg data was 21 m from a range of 17 to 24 m.

When samples included juvenile or damaged specimens not identified to species level, these were combined with a species in the lowest identical taxon or removed when more than one species was present in the lowest identical taxon in the same sample. Only individuals in samples with no species in the same taxon were left at the higher level (Coolen et al., 2018, 2015a). Since densities and weights of the seabed data were given in $m^2$, the marine growth data were also converted to weights, numbers and $cm^2$ (for colonial species) per $m^2$.

***Data analysis***

For each sample, species richness, Simpson biodiversity index (Simpson, 1949) using the diversity function from vegan package (Oksanen et al., 2019), total number of individuals and total ash free dry weight were calculated. Total observed and extrapolated species richness depends on the number of samples taken (Chao et al., 2014) and the number of samples available for the seabed and other artificial structures was much higher than for the concrete and rock dump. Therefore, to compare total species richness between substrates, the mean total species richness was calculated from subsets of the seabed data and of artificial structures data. Subsets of 39 samples were randomly selected from each of these datasets. This process was repeated 10,000 times for both, and in each repetition the subset was used to calculate total species richness in all samples as well as extrapolated species richness based on the Chao estimate (Chao, 1987) using the specpool function (Oksanen et al., 2019). These numbers were also calculated for concrete and rock dump separately, for the combined Halfweg samples and for all available samples from the seabed, Borkum Reef Grounds and the other structures combined. A Euler plot (Euler, 1768) showing important overlap in species between substrates was generated using the euler function from the eulerr package (Larsson, 2019).

For each non-colonial species in the dataset, average abundance and ash free dry weight as well as standard errors were calculated for concrete, rock dump, steel and seabed. To test for differences in abundance and biomass between samples from concrete, rock dump, steel and the seabed, generalised linear models were created, using a gaussian distribution with log-link. The residuals were assumed to be normally distributed with a mean of 0 and variance of $\sigma$.

To assess community structure, a multivariate analysis was performed. A Nonmetric Multidimensional Scaling plot was created with the metaMDS function (Oksanen et al., 2019) using the Bray-Curtis dissimilarity index and 10,000 runs (Bray and Curtis, 1957). This was used to visualise community differences as well as to assess multivariate spread to test whether the performance of permutational analysis of variance (PERMANOVA) was appropriate to test for community differences between concrete, rock dump and sand (Anderson, 2005, 2001). A PERMANOVA (10,000 permutations, Bray–Curtis

dissimilarity index) to asses differences between substrates was performed using the abundance data, using the adonis2 function (Oksanen et al., 2019).

Species status for the Netherlands (indigenous, non-indigenous, new observation) was assessed for all species observed on the Halfweg structures based on Bos et al. (Bos et al., 2016), the Dutch register of species (Naturalis and EIS, 2020) and a review of a selection of these species for the data of other structures (Coolen et al., 2018). Status reported in the latter was used in case of conflicts. Species not included in any of these publications were considered new descriptions of the species for Dutch fauna.

# RESULTS

## Species richness and uniqueness

In total, 65 species were observed on the Halfweg gravity based structure (GBS) and rock dump. This included 52 species found on the concrete GBS, 44 species on the surrounding rock dump and 32 on the steel legs. Based on the extrapolated species richness, it was predicted that a total of 83 ±11 (standard error) species are present on the combined structures of Halfweg, indicating that between 7 and 29 species have been missed in the survey (Table 1). Based on the iterative subsampling of 39 samples out of 118, the seabed held 103 observed species, which were extrapolated to 156 ±24. When including all samples, the seabed contained a total of 150 species, extrapolated to 265 ±46 species. The other structures from Coolen et al. (Coolen et al., 2018) held a total of 151 species, extrapolated to 178 ±12. Simpson diversity index was highest on the rock dump at Halfweg (0.71 ±0.03) but concrete (0.54 ±0.06) was lower than seabed (0.69 ±0.02). Lowest Simpson diversity was observed on the steel of other structures (0.34±0.02).

**Table 1: Species richness & uniqueness per substrate type**
Location: other structures include oil and gas platforms and a wind farm. Substrate: all includes all substrates sampled at the location. Species: total species richness, chao: extrapolated species richness, chao.se: standard error around the mean of extrapolated species richness, unique: number of species found only on that substrate (for concrete, rock & steel excluding samples from each other), simpson&simpson.se: mean simpson diversity index with standard error, n: number of samples. Unique species were not calculated for the subsampling of seabed and structures (Seabed39 & Structures39). Substrates include: Concrete: the GBS part of Halfweg, Rock: the rock dump part of Halfweg, Steel: the steel part of Halfweg, Halfweg: concrete, rock dump and steel combined, Borkum: Borkum Reef Grounds, Structures: oil and gas platforms & the wind farm from Coolen et al. (2018), Seabed: the MWTL seabed data.

| Location | Substrate | Species | chao | chao.se | unique | simpson | simpson.se | n |
|---|---|---|---|---|---|---|---|---|
| Halfweg | Concrete | 52 | 83.03 | 25.04 | 10 | 0.5444 | 0.0594 | 20 |
| Halfweg | Rock | 44 | 51.33 | 5.58 | 9 | 0.7103 | 0.0333 | 12 |
| Halfweg | Steel | 32 | 35.42 | 3.28 | 0 | 0.6015 | 0.0585 | 7 |
| Halfweg | All | 65 | 82.59 | 11.36 | 15 | 0.6057 | 0.0352 | 39 |
| Other structures | Rock | 92 | 124.33 | 15.25 | 39 | 0.5479 | 0.0350 | 19 |
| Other structures | Steel | 124 | 151.81 | 14.21 | 58 | 0.3380 | 0.0197 | 126 |
| Other structures | All | 151 | 177.76 | 12.40 | 75 | 0.3655 | 0.0186 | 145 |
| Borkum Reef Grounds | Rock | 48 | 73.82 | 13.89 | 18 | 0.4289 | 0.1169 | 11 |
| Seabed | Sand | 150 | 265.36 | 45.90 | 121 | 0.6877 | 0.0177 | 118 |
| Seabed | Sand 39 samples | 101.57 | 150.70 | 21.91 | #N/A | #N/A | #N/A | 39 |
| Other Structures | All 39 samples | 107.25 | 150.12 | 20.36 | #N/A | #N/A | #N/A | 39 |

Most substrate types unveiled species that were not observed on any of the other substrates (Table 1). On the concrete GBS, 10 unique species were observed when compared to Borkum, other structures and the seabed, while five out of these were also observed on the rock dump, showing that the other five of the unique species on the concrete were not found on the rock dump, nor on steel. On rock dump nine unique species were observed, out of which four species were not found on the GBS. No unique species

were observed on the steel legs. In total, 15 unique species were present on the combined Halfweg substrates. Most overlap with the Halfweg substrates was observed with the other oil and gas and wind turbine structures. Out of 52 species on concrete, 30 (58%) were also observed on the rock dump around other structures and 36 (69%) on steel of other structures. Of 44 rock dump species, 27 (61%) were present on rock dump of other artificial structures and 31 (70%) on the steel of other structures. Highest relative overlap in species was observed between steel substrates, with 26 out of 32 species (81%) on the Halfweg steel observed on steel of other structures (Figure 5). The sandy seabed showed the lowest overlap with the Halfweg substrates, of 150 species on the seabed only 10 (7%) were observed on the GBS, 6 (4%) on the rock dump and 2 (1%) on steel. When comparing natural and artificial substrates, the rocky substrates of the Borkum Reef Grounds had a relatively large overlap with Halfweg, of 48 species, 12 (25%) were also observed on the GBS, another 12 (25%) on rock dump and 10 (21%) on steel of Halfweg. Of a total of 311 species found in all available data, only seven (2%) were observed on six substrates (excluding seabed) and only the bryozoan *Electra pilosa* (<1%) on all seven substrates included.

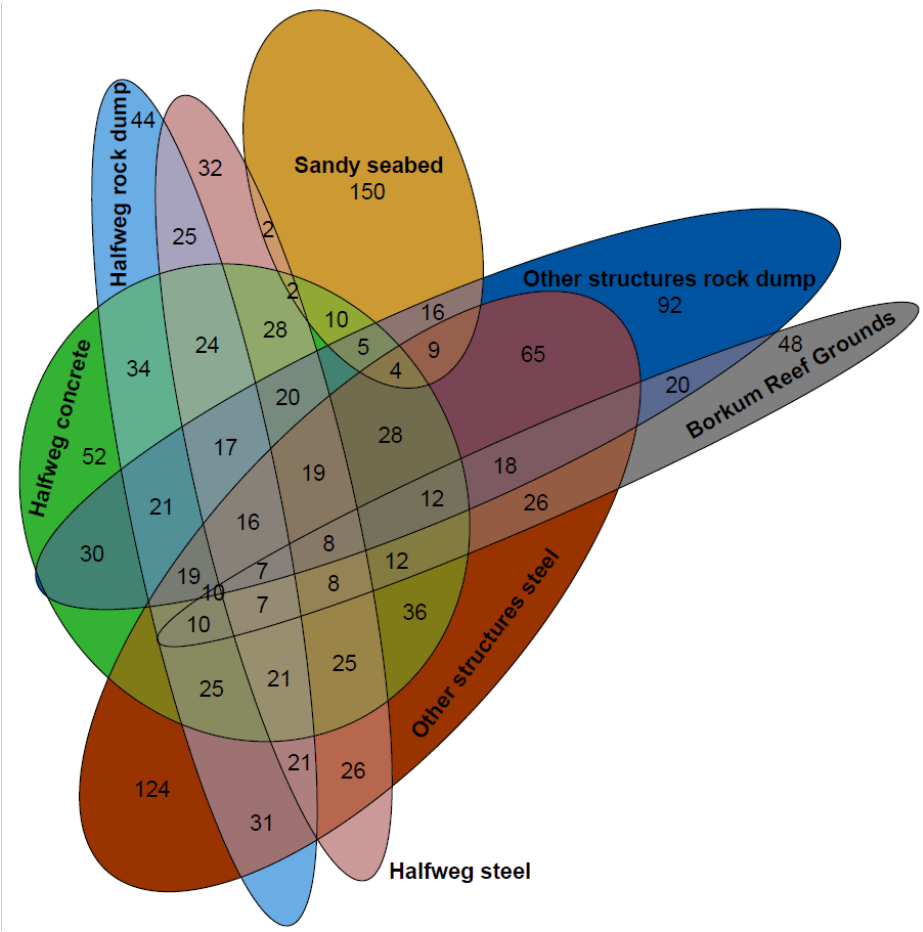


**Figure 5: Euler diagram of overlap in species between substrates**
Euler diagram presenting overlap in species between substrates (ellipses) for the strongest relations. Numbers present the total number of species per substrate (numbers in ellipse area without overlap) or shared between substrates (in the area of overlap between ellipses). Note that plotting all overlap between all combinations was impossible to visualise, resulting in missing overlap such as between the Sandy seabed and Halfweg rock dump (6 species).

Two species (amphipod *Monocorophium sextonae* and the colonial tunicate *Diplosoma listerianum*) found on Halfweg substrates were registered as non-indigenous for the Netherlands. Both species were also present on the other reefs considered. The bryozoan *Schizoporella unicornis* and sponge *Leucosolenia botryoides* were not recorded in the species lists for the Netherlands (Bos et al., 2016; Naturalis and EIS,

2020) but *L. botryoides* was reported for the other structures (Coolen et al., 2018). *L. botryoides*, although not in the Dutch species list, was reported before from the Netherlands (Langeveld et al., 2020). It has originally been described from the English Channel (Ellis et al., 1786) and as such is here considered indigenous to the Netherlands. *S. unicornis* is an indigenous species in western Europe (Ryland et al., 2014).

## Species abundance

Abundance of all species combined was significantly higher ($p<0.01$ $R^2=0.31$) on the Halfweg substrates (mean abundance 40,393 ±7,841 standard error per $m^2$) than on the surrounding seabed (2,280 ±165). Highest abundance was observed on concrete, with an average of 58,783 ±13,739 individuals per $m^2$. Arthropoda caused most of the higher abundance on the Halfweg structure, with a mean abundance of 49,499 ±10,341 individuals on concrete, 10,605 ±2,276 on the rock dump and 25,080 ±6,060 on steel (Figure 6). Within Arthropoda on the concrete, amphipods *Monocorophium acherusicum*, *Jassa herdmani*, *Phtisica marina* and *Stenothoe monoculoides* were responsible for 98% of the observed abundance. In the seabed only 654 ±51 Arthropoda per $m^2$ were observed, of which the amphipod *Urothoe poseidonis* provided 63%. In the seabed, the most abundant phylum was Mollusca, with an average of 1,020 ±163 individuals per $m^2$. Nemertea were absent from all Halfweg samples as well as the Borkum Reef Grounds. These were observed with a mean abundance of 44 ±10 on the seabed and 18 on other platforms. Echinodermata were absent on the Halfweg rock dump and steel as well as on the geogenic rocky reefs of the Borkum Reef Grounds. On the Halfweg concrete 129 ±86 Echinodermata individuals per $m^2$ were observed, lower than the 466 ±103 on other structures.

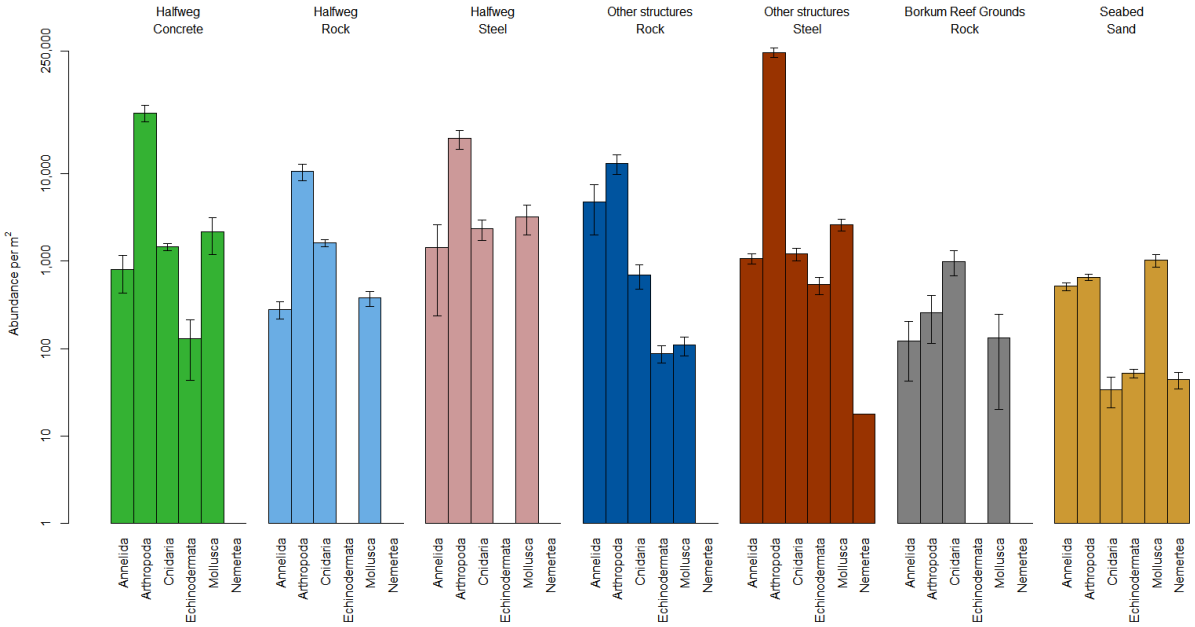


**Figure 6: Average abundance**
Bar plots showing average abundance with standard errors per $m^2$ of non-colonial species per phylum on different substrates. Y-axis in log scale. Abundance of zero shown as empty slot with continued x-axis line.

## Benthic biomass

Biomass of all species combined was significantly higher ($p<0.001$ $R^2=0.29$) on the Halfweg substrates (mean ash free dry weight 204 g AFDW per $m^2$ ±20 standard error) than on the surrounding seabed (65 ±8 g per $m^2$). No significant difference of mean weight of the rock dump fauna (247 ±37) with concrete (191 ±23) or steel (168 ±65) was found (Table 2).

**Table 2: Ash free dry weights**
Ash free dry weights (AFDW) in g per $m^2$, with mean, standard error (se), minimum (min), maximum (max), median values and total number of samples (n). Concrete, Rock & Steel substrates based only on Halfweg samples.

| Substrate | mean | se | min | max | median | n |
|---|---|---|---|---|---|---|
| concrete | 190.60 | 23.13 | 8.14 | 384.14 | 179.52 | 20 |
| rock | 246.77 | 36.77 | 101.02 | 449.21 | 192.11 | 12 |
| steel | 167.74 | 64.66 | 19.42 | 470.60 | 88.18 | 7 |
| sand | 64.58 | 7.65 | 0.48 | 368.06 | 24.19 | 118 |

The primary component of the high weights on concrete and rock was the plumose anemone *Metridium senile*, which made up 183 (96%) ±24 g AFDW per $m^2$ on concrete and 245 (99%) ±37 on rock dump (Table 3). *M. senile* also caused the high dominance of Cnidaria in most samples taken on the concrete and rock dump (Figure 7). This species was not observed on the sandy seabed. In the seabed biomass was dominated by the subtruncate surf clam *Spisula subtruncata*, with an average ash free dry weight of 35 (54%) ±7 g AFDW per $m^2$. On the Halfweg structure total Mollusca biomass was below 1 g AFDW per $m^2$ with no *S. subtruncata* while in the seabed it was an average of 50 g AFDW per $m^2$.

**Table 3. Abundance and weight per species per location per habitat**

Abundance of individual species in n per m$^2$, colonial species (with *) in cm$^2$ per m$^2$ on Halfweg and presence (P) on the other locations. Ash free dry weight in g per m$^2$ (no data for colonial species [*], *Balanus crenatus* and *Verruca stroemia*) of species observed on Halfweg and the seabed. All numbers ± standard error.

| Phylum / species | Halfweg Concrete n or cm2* | Halfweg Concrete AFDW | Halfweg Rock n or cm2* | Halfweg Rock AFDW | Halfweg Steel n or cm2* | Halfweg Steel AFDW | Seabed Sand n | Seabed Sand AFDW | Other structures Steel n | Other structures Rock n | Borkum Rock n |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Annelida | | | | | | | | | | | |
| *Aonides paucibranchiata* | 1±1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Dipolydora coeca* | 3±1.64 | 0 | 6.67±6.67 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Eulalia viridis* | 1±1 | 0.01±0.01 | 8.33±6.72 | 0.01±0.01 | 5.71±5.71 | 0 | 0 | 0 | 111.51±24.69 | 27.41±18.99 | 14.55±14.55 |
| *Eunereis longissima* | 18±6.94 | 0.01±0.01 | 5±3.59 | 0 | 0 | 0 | 2.14±0.71 | 0.35±0.17 | 35.91±20.63 | 84.21±53.87 | 3.64±2.44 |
| *Harmothoe impar* | 3±1.64 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 50.54±17.2 | 2.82±2.05 | 1.82±1.82 |
| *Lepidonotus squamatus* | 8±6.05 | 0.01±0.01 | 0 | 0 | 5.71±5.71 | 0.01±0.01 | 0 | 0 | 60.71±9.67 | 30.15±17.1 | 5.45±2.82 |
| *Mysta picta* | 0 | 0 | 1.67±1.67 | 0.01±0.01 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Phyllodoce mucosa* | 2±2 | 0 | 3.33±3.33 | 0 | 0 | 0 | 8.04±7.1 | 0.04±0.04 | 1.56±0.64 | 0 | 0 |
| *Sabellaria spinulosa* | 194±79.75 | 0.32±0.09 | 141.67±46.41 | 0.24±0.05 | 0 | 0 | 0 | 0 | 1.98±1.07 | 3658.61±2238.14 | 3.64±3.64 |
| *Syllis gracilis* | 571±295 | 0.1±0.07 | 111.67±28.44 | 0.01±0 | 1240±1113.18 | 0.12±0.12 | 0 | 0 | 22.86±10.76 | 0 | 0 |
| *Syllis vittata* | 0 | 0 | 0 | 0 | 165.71±97.27 | 0.01±0.01 | 0 | 0 | 0 | 0 | 0 |
| Arthropoda | | | | | | | | | | | |
| *Aora gracilis* | 0 | 0 | 56.67±35.75 | 0 | 5.71±5.71 | 0 | 0 | 0 | 0 | 7.37±5.12 | 47.27±45.31 |
| *Apolochus neapolitanus* | 0 | 0 | 5±3.59 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Balanus crenatus* | 45±20.36 | | 65±24.14 | | 5.71±3.69 | | 0.43±0.43 | 0 | 32.69±9.57 | 71.13±67.2 | 0 |
| *Bodotria scorpioides* | 3±3 | 0 | 1.67±1.67 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Cancer pagurus* | 11±5.71 | 0.06±0.04 | 3.33±2.25 | 0.03±0.03 | 17.14±6.8 | 0.3±0.22 | 0 | 0 | 5.79±1.17 | 1.05±1.05 | 0 |
| *Cumopsis goodsir* | 0 | 0 | 0 | 0 | 2.86±2.86 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Gitana sarsi* | 125±65.11 | 0 | 85±17.08 | 0 | 151.43±89 | 0 | 0 | 0 | 143.58±37.49 | 0 | 0 |
| *Jassa herdmani* | 8536±2384.97 | 1.8±0.57 | 1580±465.21 | 0.14±0.05 | 19691.43±5117.24 | 6.92±2.34 | 0 | 0 | 204173.34±27866.63 | 8090.9±2981.26 | 0 |
| *Melita palmata* | 1±1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Microprotopus maculatus* | 1±1 | 0 | 8.33±5.2 | 0 | 0 | 0 | 0.12±0.12 | 0 | 0 | 601.05±332.61 | 0 |
| *Monocorophium acherusicum* | 35667±8207.31 | 4.07±0.96 | 6348.33±1935.14 | 0.8±0.25 | 694.29±264.38 | 0.01±0.01 | 0 | 0 | 437.43±200.41 | 1653.83±477.1 | 43.64±24.69 |
| *Monocorophium sextonae* | 19±16.12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 469.66±213.12 | 177.29±75.06 | 0 |
| *Phtisica marina* | 2981±584.35 | 0.32±0.04 | 2081.67±305.44 | 0.35±0.05 | 1808.57±849.95 | 0.17±0.09 | 0 | 0 | 619.82±143.26 | 66.43±18.75 | 0 |
| *Pilumnus hirtellus* | 66±39.34 | 0.02±0.01 | 6.67±3.76 | 0 | 105.71±48.93 | 0.03±0.02 | 0 | 0 | 27.44±5.68 | 2.82±2.05 | 0 |
| *Pisidia longicornis* | 156±85.15 | 0.09±0.03 | 33.33±21.65 | 0.07±0.06 | 51.43±28.24 | 0.06±0.03 | 0 | 0 | 63.38±15.61 | 1148.23±649.34 | 0 |
| *Pseudocuma simile* | 1±1 | 0 | 0 | 0 | 0 | 0 | 0.98±0.38 | 0 | 0 | 0 | 0 |
| *Stenothoe monoculoides* | 1520±292.45 | 0.05±0.01 | 293.33±64.82 | 0 | 2537.14±782.25 | 0.06±0.04 | 0 | 0 | 3214.14±638.4 | 342.71±119.17 | 0 |
| *Stenothoe valida* | 1±1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 423.71±101.36 | 13.16±10.56 | 0 |
| *Verruca stroemia* | 366±228 | | 36.67±19.82 | | 8.57±4.04 | | 0 | 0 | 0.6±0.3 | 255.75±227.43 | 0 |
| Bryozoa | | | | | | | | | | | |
| *Alcyonidioides mytili** | 0 | | 25±21.62 | | 0 | | 0 | | P | P | 0 |
| *Arachnidium fibrosum** | 0 | | 38.33±36.55 | | 0 | | 0 | | P | P | 0 |
| *Bugulina turbinata** | 570±478.42 | | 6.67±2.84 | | 62.86±56.3 | | 0 | | 0 | P | 0 |
| *Callopora dumerilii** | 0 | | 25±25 | | 0 | | 0 | | P | P | 0 |
| *Conopeum reticulum** | 4±2.34 | | 331.67±329.85 | | 0 | | 0 | | P | P | P |
| *Crisularia plumosa** | 172±159.51 | | 13.33±9.95 | | 0 | | 0 | | 0 | 0 | 0 |
| *Electra pilosa** | 41±31.71 | | 20±9.53 | | 8.57±4.04 | | P | | P | P | P |
| *Microporella ciliata** | 0 | | 1.67±1.67 | | 0 | | 0 | | P | P | 0 |
| *Schizomavella linearis** | 72±37.12 | | 0 | | 57.14±47.89 | | 0 | | P | P | 0 |
| *Schizoporella unicornis** | 5±3.52 | | 11.67±11.67 | | 8.57±5.95 | | 0 | | 0 | 0 | 0 |
| *Scruparia chelata** | 32±8.13 | | 6.67±2.84 | | 5.71±3.69 | | 0 | | P | 0 | 0 |
| *Scrupocellaria scruposa** | 547±510.41 | | 26.67±9.64 | | 0 | | 0 | | 0 | 0 | 0 |

| Phylum / species | Halfweg Concrete n or cm2* | Halfweg Concrete AFDW | Halfweg Rock n or cm2* | Halfweg Rock AFDW | Halfweg Steel n or cm2* | Halfweg Steel AFDW | Seabed Sand n | Seabed Sand AFDW | Other structures Steel n | Other structures Rock n | Borkum Rock n |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Chordata | | | | | | | | | | | |
| *Diplosoma listerianum** | 601±542.61 | | 28.33±7.57 | | 651.43±368.96 | | 0 | | P | P | P |
| Cnidaria | | | | | | | | | | | |
| *Clytia hemisphaerica** | 57±31.76 | | 8.33±4.58 | | 5.71±3.69 | | 0 | | P | P | P |
| *Ectopleura larynx** | 0 | | 0 | | 42.86±42.86 | | 0 | | P | P | P |
| *Laomedea flexuosa** | 0 | | 3.33±3.33 | | 0 | | 0 | | P | 0 | 0 |
| *Metridium senile* | 1361±155.04 | 183.4±23.67 | 1580±152.53 | 245.05±36.82 | 1948.57±586.95 | 157.56±66.92 | 0 | 0 | 715.97±130.66 | 594.21±220.44 | 987.27±317.77 |
| *Obelia bidentata** | 0 | | 8.33±8.33 | | 0 | | 0 | | P | P | P |
| *Plumularia setacea** | 33±18.08 | | 1.67±1.67 | | 5.71±3.69 | | 0 | | 0 | 0 | 0 |
| Echinodermata | | | | | | | | | | | |
| *Amphipholis squamata* | 5±4.07 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 102.22±54.8 | 0 | 0 |
| *Ophiothrix fragilis* | 36±31.87 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 91.49±46.08 | 7.37±4.64 | 0 |
| *Ophiura albida* | 1±1 | 0 | 0 | 0 | 0 | 0 | 2.43±0.68 | 0.01±0.01 | 0 | 0 | 0 |
| *Ophiura ophiura* | 3±3 | 0 | 0 | 0 | 0 | 0 | 1.53±0.78 | 0.06±0.03 | 0 | 0 | 0 |
| Mollusca | | | | | | | | | | | |
| *Brachystomia scalaris* | 19±19 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 389.43±121.53 | 2.82±2.82 | 0 |
| *Epitonium clathratulum* | 363±82.54 | 0.01±0.01 | 273.33±68.37 | 0.01±0.01 | 8.57±5.95 | 0 | 0 | 0 | 0.14±0.14 | 0.94±0.94 | 0 |
| *Epitonium clathrus* | 0 | 0 | 1.67±1.67 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Euspira nitida* | 56±20.45 | 0 | 3.33±2.25 | 0 | 0 | 0 | 9.68±1.69 | 0.1±0.04 | 0 | 0 | 0 |
| *Hiatella arctica* | 1±1 | 0 | 0 | 0 | 5.71±5.71 | 0 | 0 | 0 | 3.81±2.12 | 1.88±1.29 | 0 |
| *Kellia suborbicularis* | 34±13.07 | 0 | 1.67±1.67 | 0 | 62.86±62.86 | 0.02±0.02 | 0 | 0 | 6.67±3.99 | 0 | 0 |
| *Mytilus edulis* | 1509±930.33 | 0.18±0.11 | 98.33±71.16 | 0.03±0.02 | 3100±1146.89 | 1.02±0.37 | 0 | 0 | 1728.83±322 | 32.22±15.34 | 3.64±3.64 |
| *Pusillina inconspicua* | 67±32.55 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Spiralinella spiralis* | 1±1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Venerupis corrugata* | 1±1 | 0 | 0 | 0 | 0 | 0 | 0.11±0.11 | 0.01±0.01 | 0.85±0.4 | 0.94±0.94 | 0 |
| Porifera | | | | | | | | | | | |
| *Halichondria panicea** | 1362±885.94 | | 121.67±78.72 | | 334.29±330.96 | | 0 | | P | 0 | 0 |
| *Leucosolenia botryoides** | 35±31.88 | | 0 | | 2.86±2.86 | | 0 | | P | 0 | 0 |

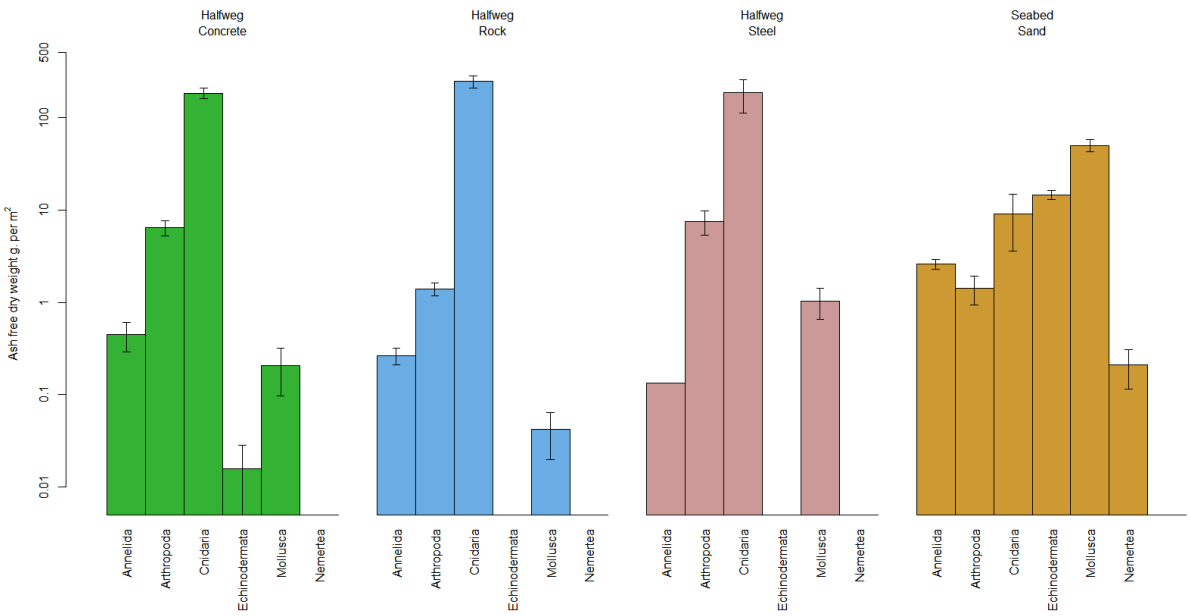


**Figure 7: Average biomass**
Bar plots showing average ash free dry weights with standard errors per $m^2$ of non-colonial species per phylum on concrete, rock dump and the sandy seabed. Y-axis in log scale. No data were available for the Borkum Reef Grounds and other structures.

The total biomass on the concrete GBS was estimated to be 262 kg ash free dry weight (based on the average weight times the available substrate), 20 kg on steel and 2,564 kg on the surrounding rock dump. Total weight of the macrofauna on the Halfweg substrates therefore was 2,846 kg. The area of seabed covered by both hard substrates was 3,617 $m^2$, resulting in a macrofauna weight of 232 kg that could have been in the seabed if Halfweg was absent.

## Community differences

The non-metric multidimensional scaling (NMDS; 2 dimensions, stress 0.11; Figure 8) of all available abundance data showed a cluster of the samples originating from all included reefs which was clearly separated from the cluster of samples of the sandy seabed. Within the cluster of reef substrates, the Halfweg substrates cluster together, with overlap from the other structures. PERMANOVA showed a significant ($p<0.001$) influence of substrate type on community structure, confirming the observed differences in the NMDS.

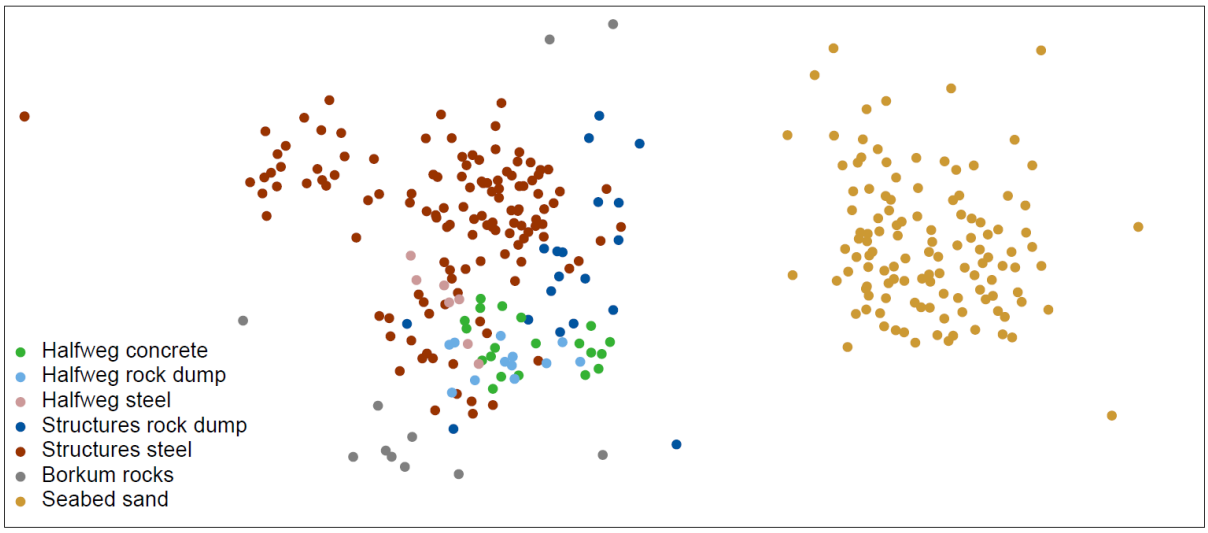


**Figure 8: Non-metric multidimensional scaling plot**
NMDS plot based on abundance data from all acquired data (Bray-Curtis dissimilarity index, 10,000 runs, stress 0.11, best solution after no convergence).

# DISCUSSION

The Halfweg structure clearly has an impact on local biodiversity and biomass. A total of 65 species was observed on Halfweg and a total of 150 in the surrounding seabed in a radius of 30 km from Halfweg. Only 10 of the Halfweg species were also observed in the seabed. Therefore, the presence of the artificial and rocky substrates of Halfweg, increased local species richness by 55 (37% compared to 118 seabed samples, 53% when compared to 39 seabed samples). On the scale of Halfweg (3,617 $m^2$), the macrofauna biomass increased by 12 times that of the biomass in the sandy seabed. This is a result of a higher biomass per $m^2$ of area available to fouling species and of the complexity of the concrete structure and rock dump, increasing the available area compared to a flat horizontal seabed (Calow, 1972; Cooper and Testa, 2001; Graham et al., 1988).

The observed high mean Simpson diversity on the rock dump and low on the concrete, is in line with observations in wind farms, where straight steel monopiles held lower Shannon diversity than the surrounding rocky natural substrates (Wilhelmsson and Malm, 2008). A similar ratio was found on the steel vs rock dump around other structures. It is, however, noteworthy that mean Simpson diversity at the Borkum reef grounds was lower than all other artificial structures in this study.

Compared to other reefs between 32 and 184 km from Halfweg, 23% of the species observed on Halfweg were unique, meaning they were not found elsewhere in the data of platforms, a wind farm and a natural reef. When only considering the concrete GBS, 10% of the species was not found on any of the other substrates, rising to 19% when excluding the Halfweg rock dump and steel from this comparison. On the rock dump a very similar percentage of 9 was not found elsewhere, 21% when excluding the GBS and steel.

Two non-indigenous species were observed on Halfweg, which with 3% is lower but similar to the percentage reported from the deep parts of the other structures (Coolen et al., 2018). Both non-indigenous species have repeatedly been reported from natural or artificial reef structures in the North Sea (Coolen et al., 2018, 2015a; De Mesel et al., 2015; Vance et al., 2009; Vincent Zintzen et al., 2007; Zintzen and Massin, 2010) and can be considered common on reefs in the North Sea. The bryozoan *Schizoporella unicornis* is considered native to western Europe (Ryland et al., 2014) but was not reported before as a living offshore specimen from the Netherlands. It is possible that the species has always been present in the Netherlands but was missed in previous surveys as has been suggested before in first observation reports for macrofauna on artificial structures the North Sea (Coolen et al., 2015b; Dias et al., 2017; Faasse et al., 2016).

## Removal options

The removal options considered by Petrogas, lead to two end scenarios:

1. The gravity based structure is fully removed and the surrounding rock dump is scattered partly across the area while the remaining rock dump is untouched;
2. The GBS is left in place and all rock dump remains untouched.

In the first scenario, all fauna that is currently present on the concrete GBS will be removed or scattered during removal, most likely resulting in the effective removal of most of the species present on the concrete. An estimated 50% of the rock dump will be placed elsewhere or dredged up (personal communication Gert de Raadt, Petrogas). When moved by crane some of the macrofauna may remain on the rock dump, although it is unlikely that the rocks will be placed in an identical orientation, likely resulting in the burial or damaging of most fauna present on the moved rock dump. Assuming 50% of the rock will remain untouched, the fauna present on these rocks will mostly stay as it is now. On a longer term, the moved rock dump is likely to be colonised by a similar community as is currently present, originating from the untouched rock dump, small hard substrates on the seabed or other source locations where the current species originate from, e.g. by colonisation by settling larvae or via migration of juveniles and adults (Coolen et al., 2020; Krone and Schröder, 2011; Luttikhuizen et al., 2019). At that point, the species richness might recover to the 44 species that have now been observed on the rock dump. This scenario will therefore result in the loss of 21 species of macrofauna that are currently present on the concrete and steel but not on the rock dump. However, four of these 21 species have also been observed in the seabed, so the nett loss of species richness to the local area is predicted to be 17 species, or more as the observed species richness is not exhaustive. No unique species could be calculated for extrapolated species richness, but given that these numbers are higher than observed richness the nett loss might be higher than 17. Since after the removal of the GBS, the rock dump will be scattered across the area, the total area of substrate available to fouling communities could remain approximately similar to what is now available on the GBS plus rock dump. Assuming this would be colonised in a similar manner as occurred for the current situation, this would then lead to a total biomass that is similar to the current total biomass.

In the second scenario everything remains as it currently is. No species will be lost due to removal or replacement activities, no rock dump is moved and biomass is not changed. The GBS and rock dump have been in place since 1996 and have possibly reached a stabile stage of succession (Oshurkov, 1992), although this has not been investigated here. Observations from other structures (Coolen et al., 2018; Krone et al., 2013; Whomersley and Picken, 2003) which originated from structures older as well as younger than Halfweg, confirm this, as they also show a *Metridium senile* dominated community at depths similar to Halfweg.

## Should the structure be removed?

This investigation of the fouling macrofauna community on a concrete structure and rock dump has been initiated by Petrogas as the company felt that the potential loss in biodiversity was worth considering in its removal decision procedure. There is no common procedure followed by oil and gas companies to assess the impact on macrofauna communities in removal procedures during platform decommissioning. Permits for North Sea oil and gas structures as well as other offshore installations such as wind farms include an obligation to remove the structure to some level (Fowler et al., 2018; OSPAR Commission, 1998). This obligation has risen from an intense debate after proposals from oil and gas companies to 'reef' certain structures in the North Sea in the past (Jørgensen, 2012). In other regions, reefing or leaving in place of decommissioned oil and gas structures is common practise (Kaiser, 2006; Quigel and Thornton, 1989). In the North Sea, it has been suggested by scientists (Fowler et al., 2018; Jørgensen, 2012; Macreadie et al., 2012) as well as other organisations (Jørgensen, 2011; Pors et al., 2011; Verbeek, 2013, 2011) to consider the leave-in-place option in decommissioning procedures.

In the Netherlands, new permits for offshore wind farm development require the developer to take measures to increase the suitable habitat for indigenous North Sea species through the creation of small and large holes and crevices and provide suitable settlement substrate (Kingdom of the Netherlands, 2019). Wind farm developers are allowed to attain this by a set of options, which include i.a. the placement of >1 m wide concrete tubes, or reef balls of a similar size. This shows that the Dutch

government is convinced that the introduction of concrete structures is beneficial for indigenous species of the Dutch North Sea. Alternatively, developers can optimise the scour protection (rock dump) design for the creation of holes and crevices available to large mobile demersal species, by use of specific sizes of rock. Both types of substrates that can be added to wind farm designs, are present at Halfweg and most likely have a similar positive effect. Any concrete introduced in a wind farm in the area is likely to attract a similar community as observed on Halfweg. Many of the species observed on the GBS, including e.g. *Balanus crenatus*, *Jassa herdmani*, *Monocorophium acherusicum*, *Mytilus edulis*, *Eulalia viridis* and *Pisidia longicornis* have also been reported for concrete wind turbine foundations in Belgium (De Mesel et al., 2015). The parts of these concrete wind turbine foundations that are near the seabed, like Halfweg, are dominated by a *Metridium senile* (De Mesel et al., 2015), as is the case on Halfweg. This species is common on most natural and artificial reef structures in the southern North Sea (Coolen et al., 2018, 2015a; Hardy, 1981; Schutter et al., 2019; van der Stap et al., 2016; V Zintzen et al., 2007) and is likely to play an important role in community structuring on these reefs (Coolen et al., 2018).

31% of the species observed on the Borkum Reef Ground rocky reef, were also observed on Halfweg, and 29% on the GBS and steel. The Borkum Reef Grounds, although currently not protected, meet the definition of the EU Habitats Directive habitat type 1170: "*either biogenic concretions or of geogenic origin. They are hard compact substrata on solid and soft bottoms, which arise from the sea floor in the sublittoral and littoral zone.*" (Coolen et al., 2015a; European Commission, 2013, 1992) and as such can be considered a valuable habitat. Since the Borkum reefs and Halfweg show a high overlap in species composition and cluster together with all reef data reported here, Halfweg could be considered as to provide a similar function as the natural Borkum Reef Grounds do.

Considering the high number of unique species on the gravity based foundation, the material overlap with nature stimulating obligations for offshore wind farms, the overlap in species composition with a habitat fitting the EU Habitats Directive habitat type 1170, and the fact that the structure has been at the current location for 25 years, no reason for full removal can be identified from a benthic macrofaunal perspective. On the contrary: removal will have a negative impact on local biodiversity and will most likely result in the loss of a significant part of the species currently present.

# CONCLUSION

Removal of the gravity based foundation of Halfweg will result in the loss of a significant number of species from the local area. Clear overlap in species composition is present between Halfweg and the Borkum Reef Grounds. Due to the scattering of rock dump after removal, local impact on macrofouling biomass is considered low. The option to leave the GBS in place as it is, will result in the highest number of species conserved to the area.

# ACKNOWLEDGEMENTS

We thank the crew of the Cdt. Fourcault (IMO 7304675; NV Seatec). Without their professional support the dives would have been impossible. We are grateful to the supporting divers, including Joost Bergsma (Bureau Waardenburg), Ben Stiefelhagen and Melchior Stiefelhagen (Get Wet Maritiem) and Klaudie Bartelink and Peter van Rodijnen (Dutch Maritime Productions). Emiel Brummelhuis, Jack Perdon and Jan Tjalling van der Wal (Wageningen Marine Research) were involved in our lab work or data-processing and we thank them for their help. The work reported in this publication was funded by Petrogas E&P Netherlands B.V.. We thank Alan Shand and Gert de Raadt at Petrogas for making this work possible. We thank Ruud Schulte and Michiel Harings at EBN for their comments on our analysis and outcome. We thank Prof. em. Han Lindeboom for commenting on our work and providing interesting viewpoints on the topic. An earlier version of this text was reviewed by Oscar Bos (Wageningen Marine Research), we thank him for his help improving the manuscript.

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