MARITIME SOLUTIONS FOR A CHANGING WORLD

#176 - SPRING 2025

TERRA ET AQUA

TRISOPLAST

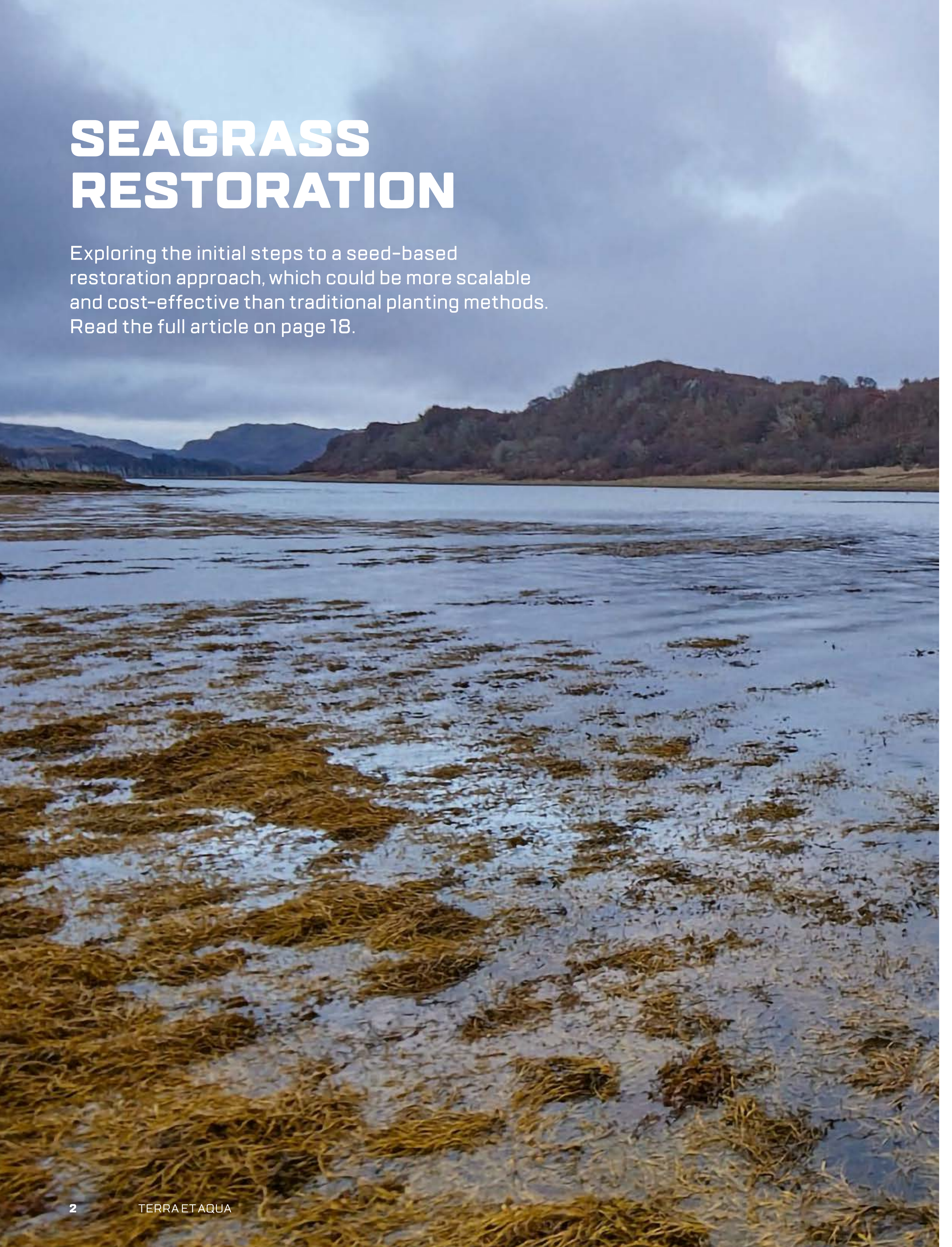
A potential alternative to clay in dyke reinforcement

SEAGRASS

Investigating large-scale restoration techniques

3D-PRINTED REEFS

ENGINEERING ARTIFICIAL REEFS TO SUPPORT BIODIVERSITY IN UAE

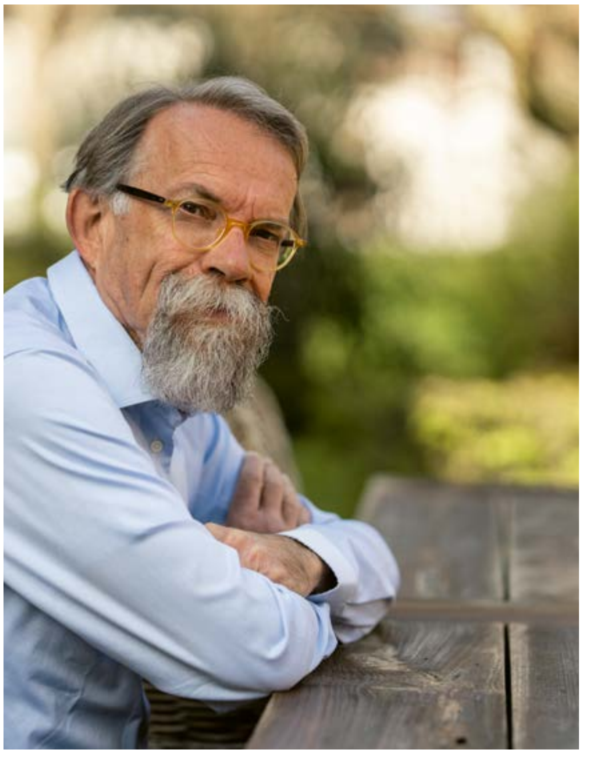


SEAGRASS RESTORATION

Exploring the initial steps to a seed-based restoration approach, which could be more scalable and cost-effective than traditional planting methods. Read the full article on page 18.

CONTENTS

BENEFITS OF BIODIVERSITY



At the beginning of this year, the world watched as destructive wildfires raged across parts of Los Angeles, burning more than 20,000 hectares of forests and homes in its path. In a region that was unusually dry after a record-breaking heat and a dry start to winter, winds blew embers for miles turning small ignitions into raging infernos. A report from World Weather Attribution (WWA) found that climate change made the hot, dry conditions that fuelled the deadly fires roughly 35% more likely.

While the challenges of climate change remain ever present, a new report from Swiss Re outlines the coastal flood risk reduction benefits of biodiversity and ecosystem services.

The study of Florida coastal areas shows how natural habitats, such as coral reefs, mangrove swamps and salt marshes, can reduce insurance loss frequency by around a half in coastal flood cases caused by higher frequency-lower severity storms.

This summer will see the second issue of IADC's new publication, *DFSI Magazine*. The theme of which will take chapter 3 of the *Dredging for Sustainable Infrastructure* book as its foundation focusing on the design process for which stakeholder involvement is of the utmost importance. Only in this way can all interests involved be properly integrated in the project design, which is necessary for the sustainability of a project.

On the topic of sustainable infrastructure, dredging and reclamation projects have played an important role in the UAE's rapid development. Meanwhile efforts are continuously made to balance progress with marine ecosystem conservation. The article on page 32 explores the development of fish domes and 3D-printed artificial reefs, highlighting their role in providing marine habitats, promoting biodiversity and supporting sustainable development.

Also in this edition, we feature the winners of last year's Waterbouwprijs (Hydraulic Engineering Prize). With almost 4,000 km of dykes in the Netherlands, finding clay of the right quality for use in reinforcement is becoming less and less available. Lian Schout's graduation thesis looks at finding a suitable alternative in the form of Trisoplast. On page 18, you'll find the work of Anne-May Alkemade, whose research forms the groundwork for innovative, large-scale seagrass restoration techniques leveraging traditional dredging methods. While seagrass restoration is increasingly recognised for its potential to enhance biodiversity and contribute to carbon sequestration, current planting methods are largely based on manual techniques, posing challenges for upscaling and implementation as nature-based solutions (NbS) within the dredging industry.

And so to a changing of the guard at IADC. I want to extend a warm welcome to Arnold de Bruijn who joins IADC in April as eventual successor to René Kolman as he hands over the helm as Secretary-General before retiring on 1 November 2025.

Frank Verhoeven
President, IADC

> **Efforts are continuously made to balance progress with marine ecosystem conservation.**


GEBR. KOK

THE ERODIBILITY OF TRISOPLAST AND CLAY

The Netherlands has almost 4,000 km of dykes. Over the past decades, a significant amount of clay has been used within these dykes for reinforcement. This layer of clay is essential as water barrier and to prevent the construction from collapsing due to erosion. Clay of the right quality is becoming less and less available, particularly because the usage requires a minimum thickness of 1.0 to 2.0 metres. Therefore, alternative materials such as Trisoplast are being researched as a suitable replacement for clay.

What is Trisoplast?

Trisoplast is a highly impermeable material comprised of a specialised clay-polymer component combined with a mineral filler such as sand, which is particularly suitable for this purpose. Developed by Tritech Solutions, which has been extensively applying this material since 1996 (Berg, 2016), Trisoplast was initially developed and successfully used for more than 30 years to seal off the top and bottom of landfills, therefore preventing the leaching of substances into the ground. Moreover, Trisoplast is also used for:

- pond sealing;
- sealing of tank pits, industrial areas, sheet pile wall pits; and
- making underground structures such as canals watertight.

The main question of this research is whether Trisoplast could be a suitable building material for dykes in the Netherlands. Within the dykes, Trisoplast can have various functions, such as lining a dyke or as an anti-piping measure replacing a heave screen. This could prevent the use of large quantities of scarce clay, as well as the use of synthetic geotextiles.

A sustainable isolation solution

As a mineral sealing material, Trisoplast is made from a mixture of sand-bentonite combined with a polymer. The standard ratio of these raw materials is approximately 88.3% sand, 11.5% bentonite and 0.2% polymer. The highly effective isolation properties of Trisoplast are attributed to its fourth ingredient – water. A robust layer of this mixture is installed on-site and can be immediately covered with a layer of sand or soil. This layer of soil of sand provides the necessary overburden. Subsequently, any water from the surrounding soil that comes into contact with the Trisoplast layer is absorbed, creating a matrix of chemical bonds between the swelling clay minerals and the dissolved polymer. The resulting strong and dense hydrogel structure offers significantly superior isolation properties compared to traditional clay liners. This swelling hydrogel fills the pores in the granular filler (e.g., sand), producing the waterproof and flexible layer that distinguishes Trisoplast (Tritech Solutions, 2023).

Simultaneously, the gritty structure of the filler imparts mechanical strength to this mineral layer. The weight of the ballast layer helps the Trisoplast layer to maintain its optimal strength by preventing excessive swelling. Trisoplast has a substantial water retention capacity and it is resistant to shrinkage. Therefore, in situations where traditional clay liners tend to dry out and crack, Trisoplast will maintain its elasticity. Together, these properties result in a durable, safe and simple liner that is quick to install. Even when it has to be fitted around numerous connections (Tritech Solutions, 2020).

Flow flumes

The clay layer in dykes ensures that the structure will not collapse due to erosion or instability. To test whether Trisoplast is erosion-resistant, various tests were conducted. These tests were carried out in two different flow flumes available at the Aqualab of Rotterdam University of Applied Sciences in the Netherlands.

The first set of laboratory tests were longitudinal flow tests that were conducted in an Armfield C4 tilting flume (see Figure 1). The flume is set at an angle of 2.51°, achieving a maximum flow velocity of 1.61 metre per second (ms^{-1}) with a water discharge of 3.16 to 3.19 litre per second (Ls^{-1}) To perform these tests, the Trisoplast and clay samples were prepared in various custom-made molds. The molds filled with Trisoplast or clay are then placed in a wooden mold within the flume, which had a slope at the front to ensure a gradual transition between the flat surface of the flume and the Trisoplast or clay sample.

The second set of tests consisted of wave loading tests and were conducted in an Armfield S6 MKI flume (see Figure 2). This flume has a maximum water discharge of 21.5 Ls^{-1} and is equipped with a flap wave generator that can generate waves. For the tests, the samples were placed in a 1:5 slope, which is comparable to the outer slope of sea dykes (TAW, 1999). During these tests, a plunging wave is generated. Because of the breaking of the waves, a significant amount of energy is exerted on the slope, increasing the probability of erosion. To perform these tests, the Trisoplast and clay samples were once again prepared in various custom-made molds. The molds filled with Trisoplast or clay are placed in a wooden mold within the flume to ensure that the samples remained in the correct position during the tests.

Preparations

To prepare the tests, the moisture content of the materials is determined. This allows for the assessment of whether the materials needed to be moisturized or dried or if they are directly suitable for the compaction of the samples. The determination of the moisture content is done by weighing the samples and afterwards placing them in the oven. The next day, the same sample is weighed again and placed back in the oven. This process is repeated until it is observed that the weight no longer decreases, indicating that all the moisture had evaporated from the sample, which on average takes 4 to 7 days. Next, the density of the materials is determined by performing a proctor test for each material.

To ensure that the materials achieved the correct degree of compaction, the volume of the various molds is determined. Next, the different materials are weighed and compacted within the molds. For clay CAT. 1 and 2, a compaction degree of 98% is maintained (TAW, 1996), and for Trisoplast, a compaction degree of 90% (standard value) is used. After compacting the materials, the Trisoplast samples are submerged in water for a week to allow the material to swell and become saturated with water (Tritech Solutions, 2020).

The cover layer of a dyke consists of an underlayer and a top layer. The underlayer serves as the sealing layer of the dyke,

FIGURE 1

Armfield C4 tilting flume.

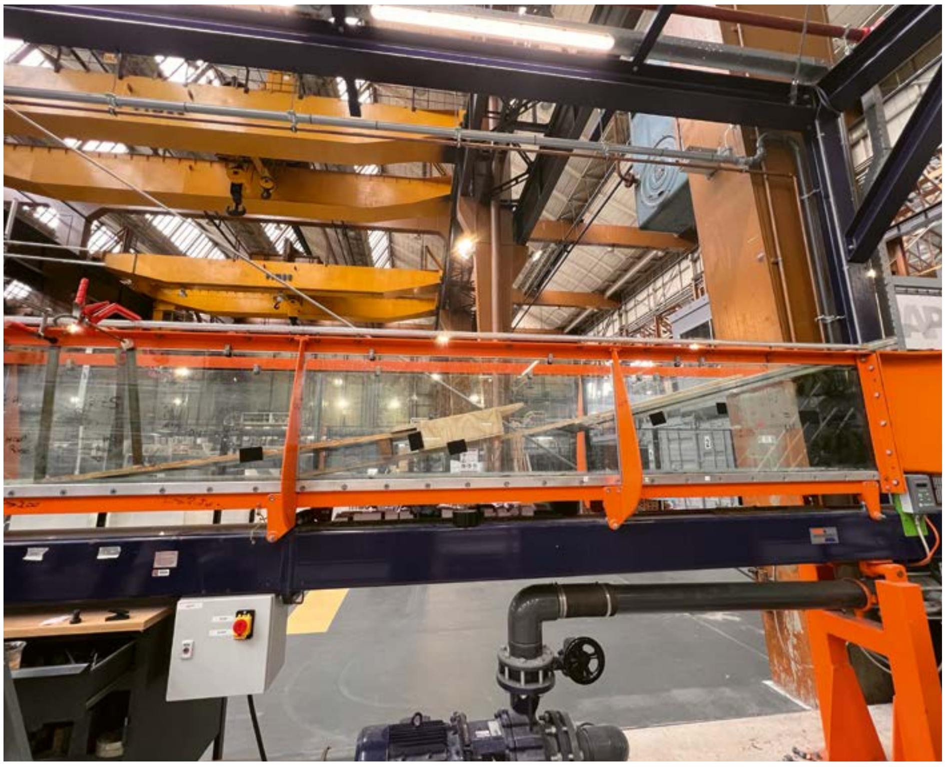


FIGURE 2

Armfield S6 MKI flume.

FIGURE 3

Defect in the samples representing the damage in the clay layer caused by wave loading.

which is usually a clay layer. The top layer often consists of grass or stone revetment. If this grass or stone revetment fails during a storm and the clay layer is exposed to the load, it is likely that this layer will be damaged. Wave loading can create holes in the grass or stone revetment. Since grass roots grow into the dyke, they can cause damage to the underlying clay layer. Therefore, a defect is also introduced in the samples to represent the form of these defects. This hole is made on the surface of the sample, 0.09 metre from the edge of the samples, as shown in Figure 3.

Laboratory tests

Heavy loamy clay erodes at a water flow velocity of 1.5 ms-1 (Hoffmans and Verheij, 2021). For this reason, the maximum achievable water flow velocity in the Armfield C4 tilting flume is examined. As mentioned earlier, a maximum water flow velocity of 1.61 ms-1 is achieved. By conducting the tests at this water flow velocity, it is hypothesised that the clay samples will begin to erode.

For the tests, various loading durations were chosen to examine whether there is a correlation between the results per duration. Thus, the tests were conducted with durations of 2, 4, 6 and 8 hours. Longer than 8 hours are not possible in this setup.

To ensure the reliability of the results, all tests were carried out in duplicate. By choosing loading durations of 2, 4, 6 and 8 hours, it was possible to complete all longitudinal flow tests in 17 working days. For each separate test, a new sample was prepared and used, allowing for the results to be comparable with each other.

For the wave loading tests, the highest significant wave is selected based on the limits of the flume. To produce this wave, a water level of 0.32 metre is applied in the flume, which varied to 0.24 metre. This was due to the flume slowly emptying during the tests.

Due to the variation in water level, the wave breaks over the entire sample. The wave that was tested has the following properties:

- Wave height [H_0] : 0.14 metre
- Wave length [L_0] : 1.35 metre
- Period [T] : 1.0 sec

These values produced a plunging wave that breaks on the Trisoplast and clay samples, increasing the probability of erosion and therefore will benefit the research. The wave loading tests were also performed in duplicate. However, unlike the longitudinal flow tests, a new sample was not prepared and was not used for each test. For this reason, the results of these tests are cumulative.

Another difference with the longitudinal flow tests is in the wave loading tests two different samples were tested side by side (see Figure 3). In this way, it is possible to observe the difference in erosion between Trisoplast, clay CAT. 1 and clay CAT. 2 during the tests. Another reason for this choice is that it was difficult to set the same wave

> **It is increasingly difficult to find enough clay that meets the required quality standards.**

load per test. This was not the case with the longitudinal flow tests, which allowed the clay and Trisoplast samples to be tested separately during the longitudinal flow tests.

Measuring the erosion

To measure erosion in the longitudinal flow tests, two methods were used. The first method involved capturing the eroded material using a filter bag. This filter bag is attached to the outflow of the flume with a hose clamp. By using this method, all the water is filtered, preventing any recoverable material from being lost. The filter bags are only capable of capturing sand and clay; the bentonite and polymer could not be captured with these filters. For this reason, the weight of the eroded material (from Trisoplast) is multiplied by 13.3%. This percentage is based on the standard ratio of Trisoplast.

The second method for measuring the eroded material involved weighing the samples before and after the tests. This approach allowed for verification that the filter had captured all the eroded material. Additionally, the moisture content of the samples was determined before and after the tests. This ensured that any increase in moisture content during the tests, which could affect the measured erosion, is accounted for. This procedure was applied to both the clay and the Trisoplast samples.

Results longitudinal flow test: Trisoplast

During the tests with Trisoplast, it was observed that two samples showed a local accumulation (Figure 4) of the material of approximately 1.5 to 2.0 cm. This local accumulation is a cluster of sand-bentonite-polymer gel where the bentonite has freely swelled, while the polymer matrix holds it together (Tritech Solutions, 2020). This explanation is confirmed by examining the local accumulation after the tests, during which it is opened. Upon opening the accumulation, no anomalies were observed in the material, making it likely that the material has freely swelled. This observation was made during the 6-hour and 8-hour tests. An explanation for this phenomenon is not known, nor why it did not occur in all tests.

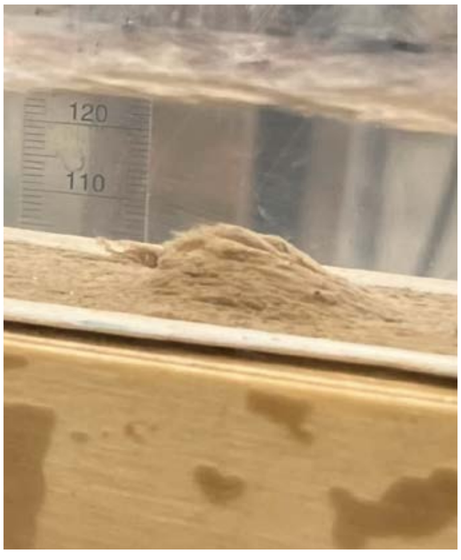


FIGURE 4

Local accumulation during the longitudinal flow tests.

Erosion Trisoplast longitudinal flow tests

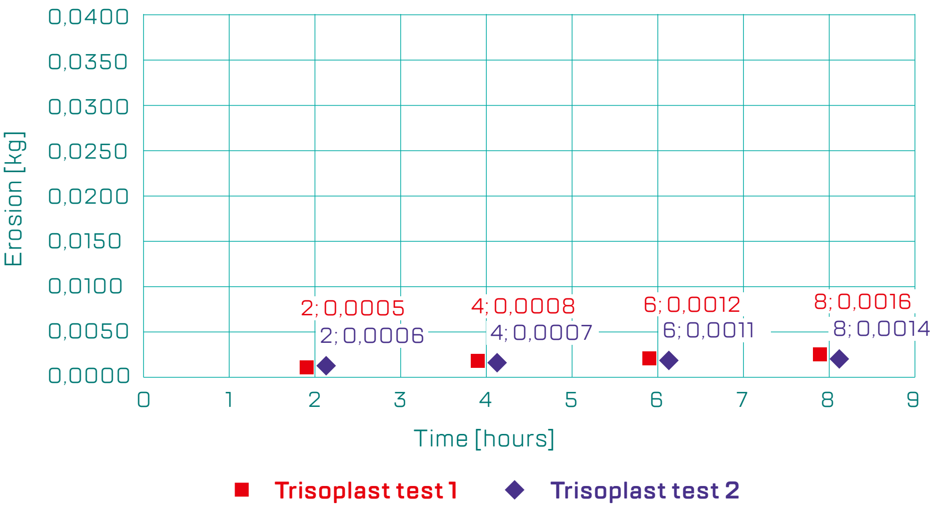


FIGURE 5

Data points erosion Trisoplast during longitudinal flow tests.

Furthermore, it was observed that a large amount of the total eroded material had been washed away during the first hour of the tests. These observations were discussed with Tritech Solutions, who explained that this occurred because the loose particles were not well adhered to the sample. For this reason, the loose particles were washed away immediately after the start of the tests.

The data points of the longitudinal flow tests with Trisoplast are shown in Figure 5. This graph shows the results per test, with the horizontal axis representing the duration of the tests and the vertical axis representing the erosion of the Trisoplast sample. This choice is made because the erosion did not occur evenly across the entire sample, making it impossible to plot the erosion in millimetres or kg/m².

As mentioned, the loose particles of the Trisoplast sample that were not well adhered eroded during the first hour of the tests. The amount of these loose particles that washed away varies per Trisoplast sample but does affect the results of the tests. Because these loose particles eroded immediately, the results of the erosion of the 2-hour tests are relatively high compared to the tests with a longer loading duration, as shown in Figure 5.

Results longitudinal flow tests: clay CAT. 1

All tests with clay CAT. 1 showed a consistent behavioural pattern, where small grooves are observed to form on the surface of the clay samples within the first hour of the tests. At the locations where these grooves are deepest, "flakes" began to erode from the sample (Figure 7).

Figure 6 presents the data points of the longitudinal flow tests with clay CAT. 1. This graph shows that the erosion of the clay samples doubles as the duration of the tests increases. This can be explained by the fact that the flow no longer moves over a smooth surface, causing more turbulence and, consequently, inducing more erosion. However, during the tests, it was noted that the erosion did not start at the edges of the clay sample but in the middle. It is possible that this is a result of the wall effects of the flume. Due to these wall effects, the velocity in the middle, between the walls, is higher than at the sides of the flume.

Erosion clay CAT. 1 longitudinal flow tests

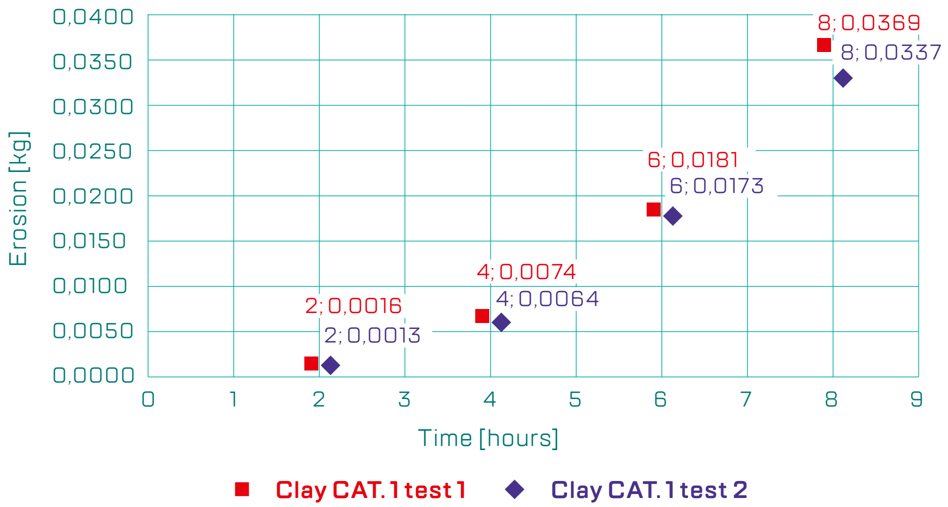


FIGURE 6

Data point erosion clay CAT. 1 during longitudinal flow tests.

FIGURE 7

Erosion clay CAT. 1 during longitudinal flow tests.

Results longitudinal flow tests: clay CAT. 2

During the tests with clay CAT. 2, it was observed that the samples in both 8-hour tests eroded significantly more than the samples did in the 6-hour tests. For this reason, the clay samples were reclassified by an independent laboratory after the tests. The results of this reclassification showed that the clay samples with an 8-hour loading duration are not equivalent to clay CAT. 2 but to CAT. 3. Since the research focuses on the differences between the erodibility of Trisoplast and clay (specifically clay CAT. 1 and clay CAT. 2), the data points from the 8-hour tests were excluded from the results.

Additionally, after five hours of testing, the clay samples showed such a significant amount of erosion that the water became turbid. This made it impossible to record observations.

As previously mentioned, the data points from the 8-hour tests were excluded, leaving only the results from the 6-hour tests shown in Figure 8. This graph shows that the results of both tests differ by 0.009 kg. These observations are remotely the same as recorded with clay CAT. 1. The only difference is that the erosion in clay CAT. 2 started in the first hour, while the first "flakes" of the CAT. 1 clay sample did not erode until the second hour.

Comparison of different materials: longitudinal flow tests

To determine which material is more erosion-resistant, the results of Trisoplast, clay CAT. 1 and clay CAT. 2 were compared (Figure 9). This comparison is made by using, for Trisoplast, the test with the most erosion, and for clay CAT. 1 and clay CAT. 2, the test with the least eroded material. By comparing these tests results the ratio between the erosion of Trisoplast and clay CAT.1 and CAT.2 is shown in the most unfavourable way. Since only one data point is recorded for the tests with clay CAT. 2, the following comparison was made with only Trisoplast and clay CAT. 1.

Figure 10 presents a comparison made between the erosion of Trisoplast and clay CAT. 1. This was done by comparing the results of test 2 of Trisoplast with test 1 of clay CAT. 1, within a time interval of 2 hours. In this graph, the horizontal axis represents the duration of the tests and the vertical axis represents the ratio of Trisoplast eroded to clay CAT. 1. The following applies to this graph:

By plotting the results of the tests, it shows that with a loading duration of 2 hours, Trisoplast erodes relatively more. This occurs

Erosion clay CAT. 2 longitudinal flow tetsts

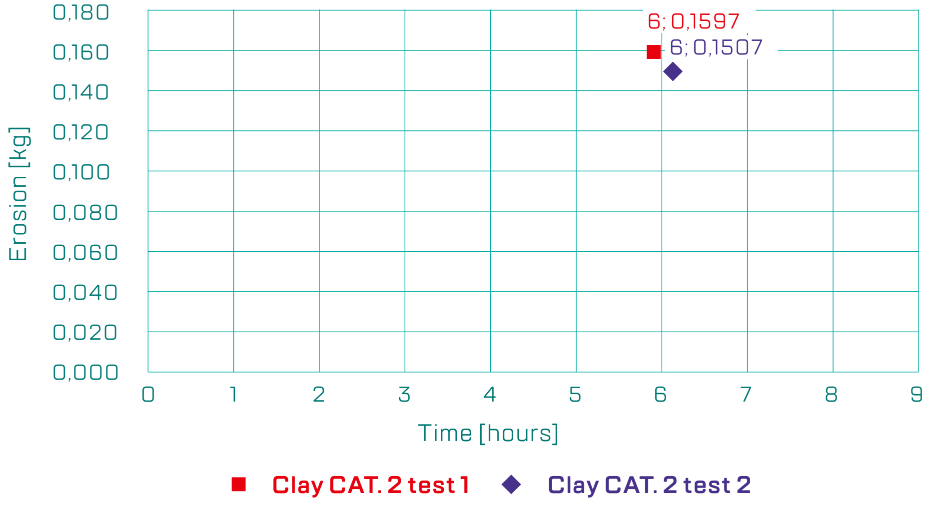


FIGURE 8

Data points erosion clay CAT. 2 during longitudinal flow tests.

Erosion Trisoplast, clay CAT. 1 en clay CAT. 2 longitudinal flow tests

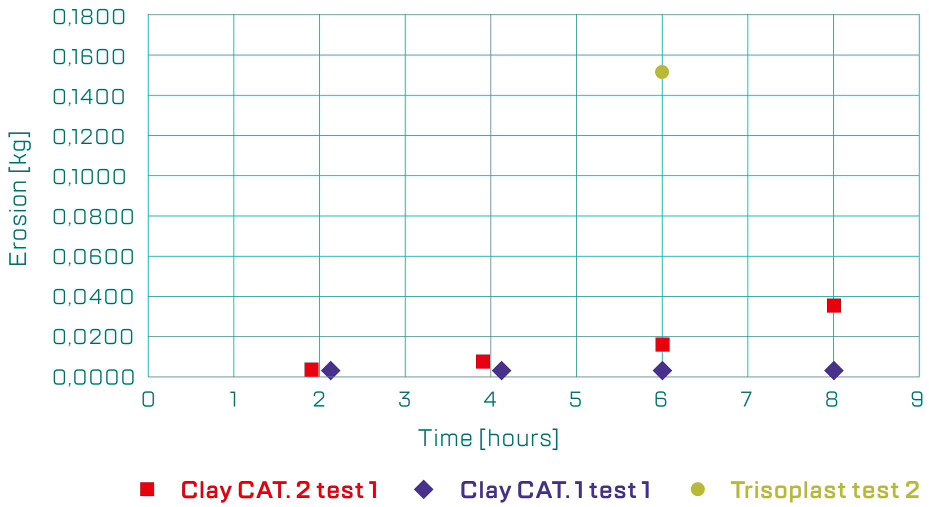
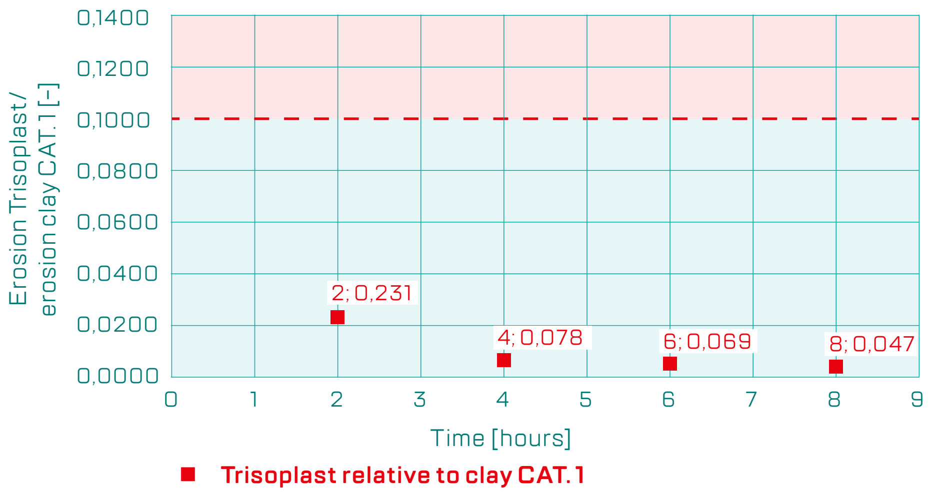


FIGURE 9

Data points erosion Trisoplast, clay CAT. 1 and clay CAT. 2 during longitudinal flow tests.

Trisoplast relative to clay CAT. 1 longitudinal flow tests



Erosion Trisoplast/ erosion clay CAT. 1 [-]	Meaning
>1.0	Erosion Trisoplast > erosion clay CAT. 1
1.0	Erosion Trisoplast = erosion clay CAT. 1
<1.0	Erosion Trisoplast < erosion clay CAT. 1

FIGURE 10

The ratio of erosion of Trisoplast relative to clay CAT. 1 during longitudinal flow tests.

> **An alternative is being researched for the use of clay as a sealing layer on dykes.**

because, at the beginning of the test, the Trisoplast sample exhibits a lot of erosion due to the washing away of loose particles. It also shows that as the test duration increases, the erosion of Trisoplast relative to the erosion of clay CAT. 1 decreases. An explanation for this is that, during the erosion of the clay sample, more turbulence develops in the flow, leading to more erosion. The same turbulence can also occur with Trisoplast. However, this turbulence has a lesser effect on the Trisoplast sample than on the clay sample. Thus, in this situation, it can be concluded that Trisoplast is more erosion-resistant than both clay CAT. 1 and clay CAT. 2 during the longitudinal flow tests.

Results of wave loading tests: Trisoplast

Similar to the longitudinal flow tests, a large amount of the total eroded material was washed away during the first hour of the tests. The explanation for this is also that the loose particles that were washed away were not well adhered to the Trisoplast sample.

The results of the tests with Trisoplast are shown in Figure 11. The results in the graph show that the longer the tests lasted, the less additional material eroded. An explanation for this is that the bentonite-polymer threads only form when erosion begins to occur. Additionally, these tests do not have a constant load, such as the flow in the longitudinal flow tests, on the samples. The wave loading that impacts the samples is more of a dynamic load, allowing the bentonite-polymer threads to remain more intact. This could result in less erosion of the material.

Results of wave loading tests: clay CAT. 1

One of the clay samples of CAT. 1 exhibited significantly more erosion during test 2 than the other clay samples (including the clay samples of CAT. 2). For this reason, this clay sample was also reclassified. The reclassification showed that the liquid limit of the clay sample was 44.65%. According to the standard plasticity chart, clay CAT. 1 must have a liquid limit of at least 45%. Since the liquid limit of this clay sample was below 45% (and therefore does not meet CAT. 1 standards) and the results deviated substantially from the other obtained results, it was decided not to include the data points from test 2 of clay CAT. 1 in the results.

During the tests, it is noted that in the first clay sample, most of the erosion occurred at the edges of the sample and at the hole

Erosion Trisoplast wave loading tests

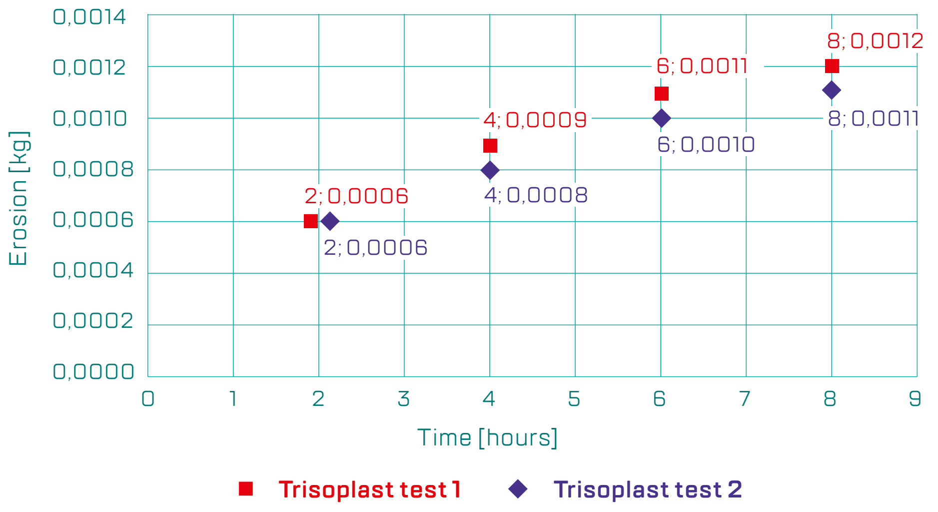


FIGURE 11

Data point erosion Trisoplast during wave loading tests.

Erosion clay CAT. 1 wave loading tests

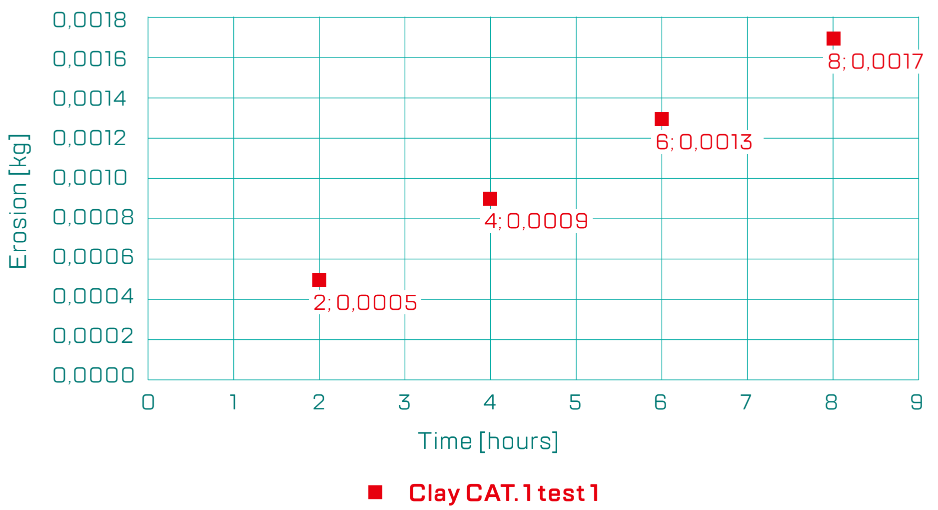


FIGURE 12

Data points erosion clay CAT.1 during wave loading tests.

FIGURE 13

Clay CAT. 1 sample during test 1.

made in the surface. This may be because the clay sample does not have a smooth surface, causing turbulence in the water. This turbulence results in more erosion of the material, which was also visible in test 2. As mentioned earlier, the data points from test 2 of clay CAT. 1 were not included in Figure 12. The clay sample in this test showed substantially more erosion than the clay sample in test 1. An explanation for this phenomenon can be that during test 2, the clay sample was positioned on the side where the metal rod is attached to the flume. This rod caused more turbulence on top of the wave loading, resulting in a hole in the clay sample as shown in Figure 13. According to the theory of Pilarczyk, turbulence has a significant effect on stability, leading to increased erosion in the clay sample (Pilarczyk and Breteler, 1988).

Results of wave loading tests: clay CAT. 2

Figure 14 shows the results of the wave loading tests with clay CAT. 2. This graph shows that erosion increases with each measurement point. This occurs with 0.0003 to 0.0007 kg per time interval. During these tests, most of the material eroded at the edges of the clay sample and at the hole made in the sample. Similar to the Trisoplast and clay CAT. 1 samples, turbulence in the water is caused by the hole. However, it can be concluded that both Trisoplast and clay CAT. 1 are more resistant to this turbulence than clay CAT. 2.

Comparison of different materials: longitudinal flow tests

Similar to the longitudinal flow tests, the different materials were compared for the wave loading tests. For this comparison, the test with the most eroded material for Trisoplast was chosen, while for clay CAT. 2, the test with the least amount of erosion was selected. By comparing the results in this way, the comparison is based on the most unfavourable situation for Trisoplast. Furthermore, for clay CAT. 1, only one data point was obtained, which is also the result used for comparison. Figure 15 presents the comparison of the different materials. The graph shows that the results of the test with clay CAT. 2 shows more erosion than the findings from the clay CAT. 1 sample. For this reason, the following comparison was made, comparing Trisoplast with clay CAT. 1. This was done because the comparison between Trisoplast and clay CAT. 2 gives a favourable result for Trisoplast while looking at the least favourable result for Trisoplast.

The comparison between Trisoplast and clay CAT. 1 is illustrated in Figure 16. In this graph, with the loading duration of the tests on the horizontal axis and the erosion of Trisoplast relative to clay CAT. 1 on the vertical axis, it can be seen that during the tests with a loading duration of 2 hours, the Trisoplast sample eroded more than the clay sample. As previously mentioned, this phenomenon occurs because all loose particles erode at the beginning of the test. This phenomenon was not observed in the clay sample. As the loading duration increases, it can be seen that Trisoplast erodes less relative to clay CAT. 1. For example, with a loading duration of 4 hours, the erosion of Trisoplast and clay CAT. 1 is equal, and with loading durations of 6 and 8 hours, Trisoplast eroded less compared to clay CAT. 1.

By comparing the results in this graph, it may appear that the Trisoplast sample is less erosion-resistant during the test with a loading duration of 2 hours. However, the washing away of loose particles from the Trisoplast sample cannot be included in the erosion, as these particles wash away at the first contact with water. Therefore, the comparison between the erosion of Trisoplast and clay CAT. 1 represented in Figure 16, is less favourable for Trisoplast than it actually is. Since the results of the wave loading are cumulative, all values in this graph should be adjusted downward. However, the factor by which this should be done has not been examined. Despite the fact that this factor has not been examined and applied to the results in the graph, it can still be concluded that Trisoplast is more erosion-resistant than clay CAT. 1 after a loading duration of 4 hours.

Conclusion

During the longitudinal flow tests, the degree of erosion of Trisoplast and clay CAT. 1 and CAT. 2 was investigated. Various tests were conducted with loading durations ranging from 2 hours to 8 hours with time intervals of 2 hours, each test starting with a new sample. Clay CAT. 2 was also tested under longitudinal flow, but for this material, only the 6-hour tests were conducted. The results of the erosion that occurred during the tests are:

- For Trisoplast, a minimum of 0.0005 kg after 2 hours to a maximum of 0.0016 kg after 8 hours;
- For clay CAT. 1, a minimum of 0.0013 kg after 2 hours to a maximum of 0.0369 kg after 8 hours; and
- For clay CAT. 2, a minimum of 0.1507 kg and a maximum of 0.1597 kg, both after 6 hours.

Erosion clay CAT. 2 wave loading tests

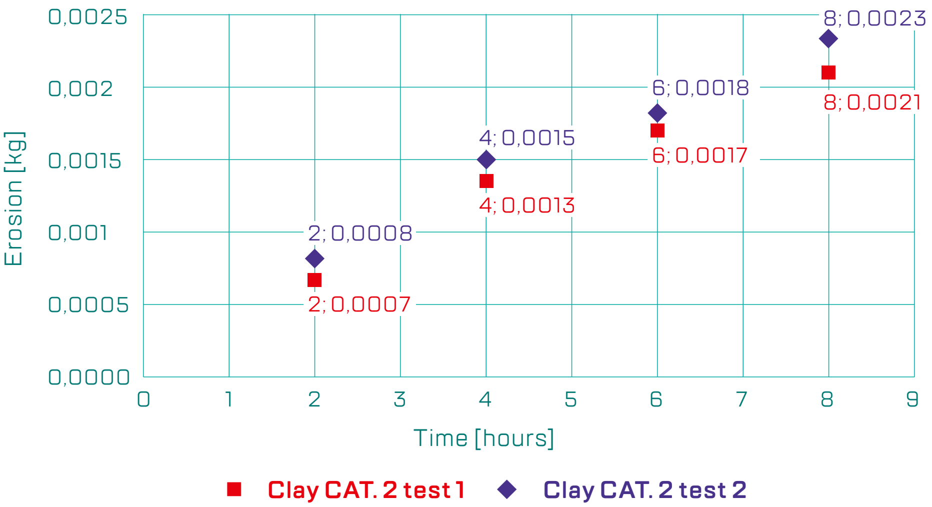


FIGURE 14

Data point erosion clay CAT. 2 during wave loading tests.

Erosion Trisoplast, clay CAT. 1 and clay CAT. 2 wave loading tests

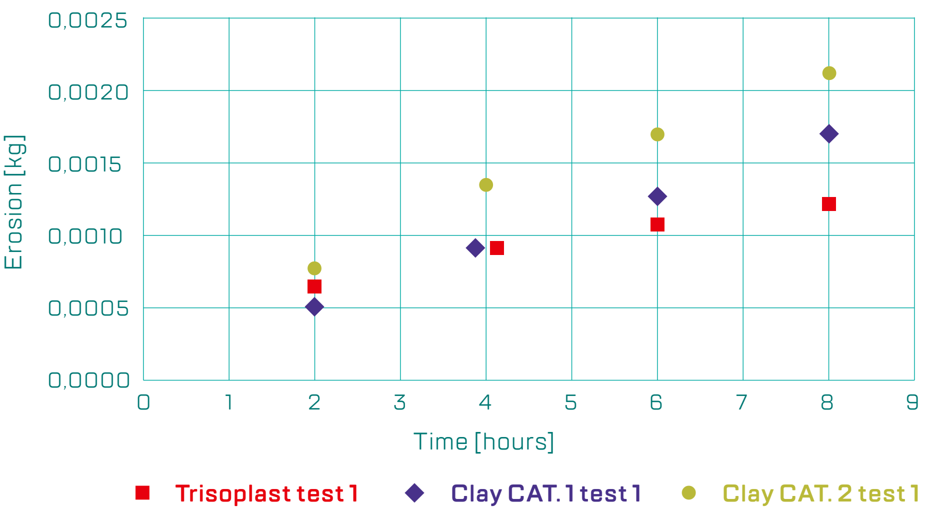


FIGURE 15

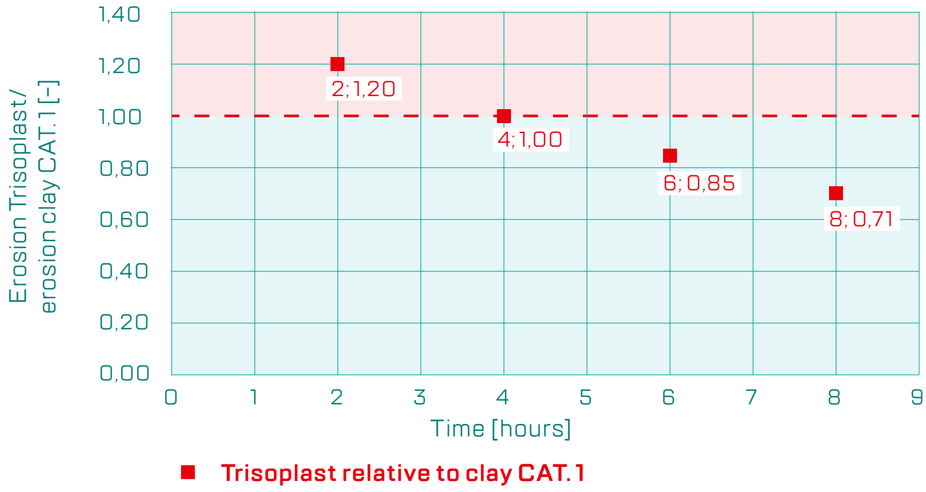
Data points erosion Trisoplast, clay CAT. 1 and clay CAT. 2 during wave loading tests.

To measure the degree of erosion that Trisoplast, clay CAT. 1, and clay CAT. 2 experience during wave loading, various tests were conducted with loading durations ranging from 2 hours to 8 hours with time intervals of 2 hours, similar to the longitudinal flow tests. However, in the wave loading tests, a new sample is not used for each test; instead, the sample is placed back in the setup after each measurement. As a result, the results obtained from these tests are cumulative.

- For Trisoplast, a minimum of 0.0006 kg after 2 hours to a maximum of 0.0012 kg after 8 hours;
- For clay CAT. 1, a minimum of 0.0005 kg after 2 hours to a maximum of 0.0017 kg after 8 hours; and
- For clay CAT. 2, a minimum of 0.007 kg after 2 hours to a maximum of 0.0021 kg after 8 hours.

For this research, the main question was "Can Trisoplast also be used in dykes in the Netherlands?" To answer this question,

Trisoplast relative to clay CAT. 1 wave loading tests

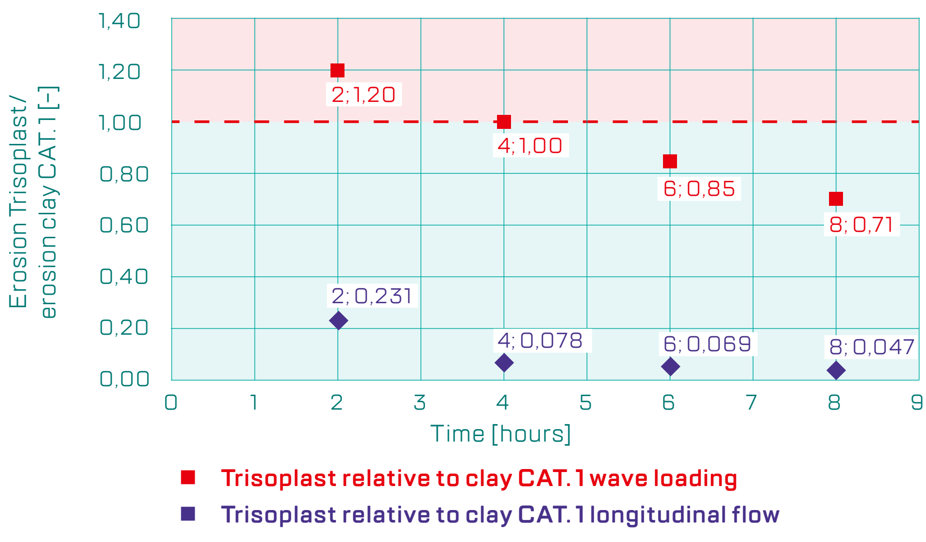


Erosion Trisoplast/ erosion clay CAT. 1 [-]	Meaning
>1.0	Erosion Trisoplast > erosion clay CAT. 1
1.0	Erosion Trisoplast = erosion clay CAT. 1
<1.0	Erosion Trisoplast < erosion clay CAT. 1

FIGURE 16

The ratio of erosion of Trisoplast relative to clay CAT. 1 during wave loading tests.

Trisoplast relative to clay CAT. 1 longitudinal flow tests and wave loading tests



Erosion Trisoplast/ erosion clay CAT. 1 [-]	Meaning
>1.0	Erosion Trisoplast > erosion clay CAT. 1
1.0	Erosion Trisoplast = erosion clay CAT. 1
<1.0	Erosion Trisoplast < erosion clay CAT. 1

FIGURE 17

The ratio of erosion of Trisoplast relative to clay CAT. 1 during longitudinal flow tests and wave loading tests.

Figure 17 shows the ratio of the erosion of Trisoplast relative to clay CAT. 1. Despite the fact that both Trisoplast and clay CAT. 1 were tested under the same loading conditions in the longitudinal flow tests, where turbulence in the flow was created for both materials, this graph shows that Trisoplast erodes less compared to clay CAT. 1.

In the wave loading tests, the erosion of Trisoplast in the 2-hour test is higher compared to clay CAT. 1. This phenomenon is a result of the erosion of loose particles from the Trisoplast sample. As the tests have longer loading durations, it can be seen that Trisoplast erodes less compared to clay CAT. 1 under the same load. By analysing the results illustrated in the graph below, it can be concluded that Trisoplast is more erosion-resistant than clay CAT. 1, making it promising to conduct further research on the application of Trisoplast as a sealing layer in dykes.

Discussion

In the present study, the difference in erodibility between Trisoplast and clay during longitudinal flow tests and wave loading tests was investigated, with all tests conducted in duplicate. However, tests conducted in duplicate do not provide sufficient reliability to definitively determine whether Trisoplast is a suitable alternative as a sealing layer in dykes.

To compare the findings from this study with previously obtained results, similar studies were reviewed. For the longitudinal flow tests with Trisoplast, a study was found where the results showed more erosion than the findings in this report. The reason for this difference cannot be explained, as both studies used the same preparation. However, a different test setup was used in both studies, which may explain the difference in erosion. Additionally, a different clay density may have been assumed in both studies. This report found that the density for clay and clay CAT. 2 differs from values in the literature. This difference cannot currently be explained but may have an impact on the erosion.

Furthermore, the erosion of Trisoplast in both the longitudinal flow tests and wave loading tests, with a loading duration of 2 hours, is relatively high compared to the erosion that occurs with a loading duration of 8 hours. This phenomenon causes Trisoplast to exhibit more erosion than clay in the wave loading tests with a shorter loading duration.

Results showed Trisoplast is more erosion-resistant than clay.

The moisture content of the samples was determined before and after each test. During the determination of the moisture content, the maximum difference for clay was measured at 1.3% (for CAT. 2), and for Trisoplast, this difference was 0.5%. This may have an impact on the results obtained in this study.

Additionally, some clay samples in this study were reclassified after exhibiting abnormal behaviour during the tests. This reclassification revealed that not all clay samples were correctly classified. This may be due to the fact that the clay was delivered in different bags, not all of which were classified. As a result, it is possible that the clay samples that were not reclassified were incorrectly classified, which means that the measured results may not belong to the correct erosion class.

Finally, to date, no fixed value is known for when clay erosion classes begin to erode. Clay is classified into CAT. 1, CAT. 2, or CAT. 3 based on the liquid limit, sand content and plasticity index. This classification does not take into account the loading conditions that the different erosion classes can withstand before erosion occurs.

Recommendations

For this research, it is essential to collect sufficient data on the erodibility of Trisoplast and clay. With this data, it can be advised in the future whether Trisoplast is a suitable alternative to clay as a sealing layer in dykes. In the present study, it was concluded that Trisoplast is potentially promising for further research, with several improvements to be considered.

The tests conducted in this study should be repeated multiple times to increase the reliability of the results. The same preparation and test setup should be used. By consistently using the same method, the results can be better compared, enabling the potential application of statistics. It is also relevant to rinse the samples with a very low flow rate before conducting tests with Trisoplast. This way, all loose particles are washed away, which may yield more favourable results for Trisoplast in the 2-hour duration tests.

In addition to repeating the tests under the same loading conditions as in this study, new tests should be conducted with different parameters. Consider longer loading durations, higher flow velocities in the longitudinal flow tests, or higher waves in the wave loading tests. These tests can provide more insight into the erodibility of Trisoplast compared to clay. Furthermore, the influence of increasing moisture content should be taken into account during the analysis of the results. The density of the clay used for the tests should also be considered.

Before conducting these tests, it is advisable to classify all samples to be tested beforehand. This can reduce anomalous results by clearly identifying which erosion class of clay is being tested. It also ensures more consistency and comparability of the results. Additionally, for future research, it is efficient to establish a fixed value for the loading conditions that the clay samples can withstand before erosion occurs. This allows for more targeted and consistent testing.

Lian Schout receiving the 2024 Waterbouwprijs (Hydraulic Engineering Prize) for her graduation assignment.

Summary

Due to the large number of dykes in the Netherlands, it is becoming increasingly difficult to find enough clay that meets the required quality standards. Therefore, an alternative is being researched for the use of clay as a sealing layer on dykes, specifically Trisoplast.

Trisoplast is comprised of a specialised clay-polymer component combined with a mineral filler, with sand being particularly suitable for this purpose.

The main question of this research is whether Trisoplast can also be used in dykes in the Netherlands. To answer this question Trisoplast and clay CAT. 1 and 2, were tested in Rotterdam's University of Applied Sciences' aqualab. Here, longitudinal flow and wave loading tests were conducted.

Results showed Trisoplast eroded only 4.7% of the amount eroded by clay CAT. 1 in longitudinal flow tests and 71% in wave loading tests. Trisoplast is more erosion-resistant than clay, warranting further investigation for use in dykes.

Lian Schout

Lian, a graduate of the Rotterdam University of Applied Sciences, won the 2024 Waterbouwprijs (Hydraulic Engineering Prize) in the HBO category with her graduation project with supervision from Antea Group and Tritech Solutions. She is currently working as a junior project engineer at Boskalis Nederland on a project called Meanderende Maas, which is a reinforcement of a dyke near the Maas, between Ravenstein and Lith.

References

Berg S. (2016)
Protocollen Trisoplast [Protocols Trisoplast]. Grondmij Nederland B.V., Houten, The Netherlands.

Hoffmans G. and Verheij H. (2021)
Scour manual. CRC Press/Balkema, Leiden, The Netherlands.

Pilarczyk K. and Breteler M. (1988)
Dikes and revetments. Ch. 16. Alternative revetments. Delft Hydraulics & Rijkswaterstaat, Hydraulic Engineering Division, Delft, The Netherlands.

TAW (1996)
Technisch rapport klei voor dijken [Technical report clay for dykes]. Technisch adviescommissie voor de waterkeringen. Delft, The Netherlands.

TAW (1999)
Leidraad Zee-en Meerdijken [Guidelines for Sea and Lake Dikes]. Technische Adviescommissie voor de waterkeringen, Delft, The Netherlands.

Tritech Solutions (2020)
Trisoplast: minerale afdichting [Trisoplast: mineral sealing]. Trisoplast, Velddriel, The Netherlands.

Tritech Solutions (2023)
Wat is Trisoplast? [What is Trisoplast?] https://www.trisoplast.com/nl/wat-is-trisoplast/innovatie/

UPSCALING SEAGRASS RESTORATION WITH INSIGHTS FROM SEED-SEDIMENT DYNAMICS

Seagrass restoration is increasingly recognised for its potential to enhance biodiversity and contribute to carbon sequestration. However, planting methods are largely based on manual techniques, posing challenges for upscaling and implementation as nature-based solutions (NbS) within the dredging industry. To address this, techniques to combine sediment nourishments with seed-based seagrass restoration are explored. Seed settlement behaviour is investigated via laboratory experiments, analysing seed settling velocities and distribution in various sediment concentrations, revealing the importance of grain size and sediment dynamics. These findings lay the groundwork for innovative, large-scale restoration techniques leveraging traditional dredging methods, with pilot projects planned for 2025.

Seagrass restoration

Seagrasses are marine flowering plants that contribute significantly to coastal ecosystems by sequestering carbon in their rhizome root systems, stabilising sediments and providing critical habitat for marine biodiversity (Duarte and Krause-Jensen, 2017; Hansen and Reidenbach, 2012; Infantes et al., 2022; Mtwana Nordlund et al., 2016) These plants thrive in shallow coastal waters across various climates, from temperate to tropical regions. Among the many species, *Zostera marina*, is a species known to produce large amounts of seeds that can be harvested easily (Kilminster et al., 2015; Marion and Orth, 2008). It is prevalent in the Northern Hemisphere and serves as the focus of this research on scalable restoration methods (Short et al., 2007).

Over recent decades, seagrass habitats have experienced substantial declines (Waycott et al., 2009). This degradation disrupts the positive feedback loop that seagrass ecosystems depend on for their survival (van der Heide et al., 2011). Seagrasses stabilise sediments with their root systems, reducing turbidity and resuspension while creating clearer waters that foster further growth. When this loop is disturbed, previously

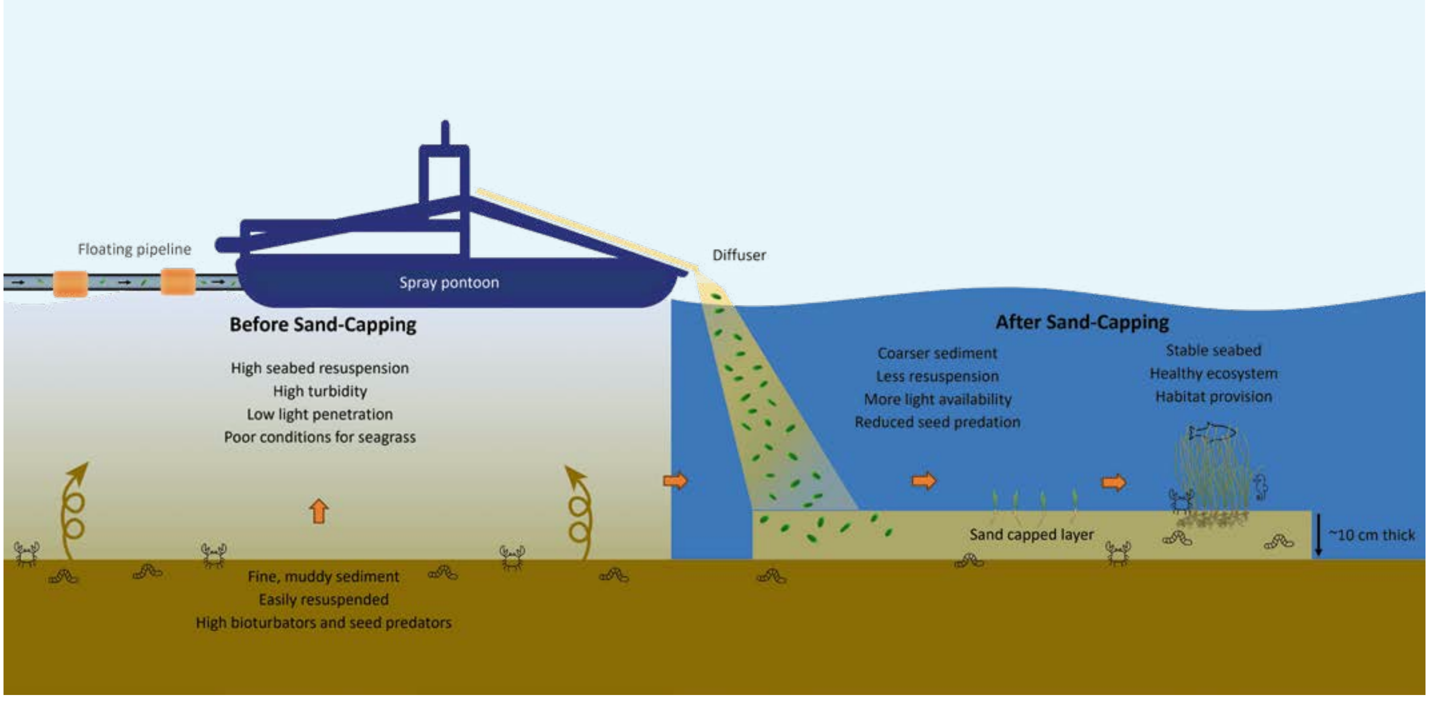


FIGURE 1

Visualisation of the effects of sand-capping technique.

thriving seagrass areas become unsuitable for natural regeneration. To address this, restoration strategies should focus on restoring the physical and ecological conditions that enable seagrasses to regenerate and sustain themselves.

Sand-capping technique

Sand-capping, a method of placing a thin-layer of coarser sand on top of the existing bed, has emerged as a promising technique to enhance seagrass restoration by reducing sediment resuspension and improving light conditions. Flindt et al. (2022) conducted laboratory experiments demonstrating that a 10 cm layer of sand can significantly reduce resuspension compared to uncapped beds and improve conditions for seagrass growth. This method also increases erosion thresholds, enhancing the anchoring capacity for root vegetation. Oncken et al. (2022) extended this research with large-scale field tests in Denmark, applying a 10 cm sand cap in two locations. The decades of eutrophication had led to impoverished benthic fauna and organic-rich muddy sediments quickly resuspended. The sand-cap stabilised the mud without mixing the sand-mud interface after one year. The associated lower resuspension of fine particle improved light conditions in the overlying water. These findings highlight the potential benefits of thin-layer capping in environments where seagrass meadows previously existed but cannot naturally regrow due to current turbidity conditions and resuspension.

Despite advancements in manual restoration methods such as hand broadcasting seeds in large-scale projects like those in Chesapeake Bay, these techniques remain highly labour-intensive and limited by low seed germination rates, typically below 4%. Alternative methods, including Bags of Seagrass Seeds (BoSS)-line, Buoy Deployed Seeding (BuDS), and Dispenser Injection Seeding (DIS), have improved germination rates to as high as 11.4% (Govers et al., 2022; Gräfnings et al., 2023; Unsworth et al., 2019), but still depend heavily on manual effort. Similarly, shoot-based transplantation, which can achieve survival rates of 30-40% (Bayraktarov et al., 2016; van Katwijk et al., 2016), usually requires divers to manually plant shoots and seedlings on the seabed. A process that is both time-consuming, resource intensive and undesirable due to safety standards.

Challenges of seed-based seagrass restoration

A major challenge lies in the current unavailability of large-scale seed cultivation in nurseries. Wild seagrass beds remain the primary source of seeds, necessitating careful collection practices to ensure the health and sustainability of donor beds. Harvesting seeds from wild beds is labour-intensive, has legal restrictions and the limited availability of healthy donor sites further constrains restoration efforts. To address this, various initiatives are exploring innovative solutions, such as mechanical seed harvesting and the establishment of seed nurseries, which could provide a more sustainable supply in the future. The scarcity of seeds underscores the critical importance of maximising seed protection and germination rates when developing new restoration techniques.

A recent study explored the synergistic effects of combining shoot-based restoration with sand-capping. Infantes (2021) conducted a field study capping a one-hectare area at 1.3-1.9 m depth to test its potential to reduce resuspension and promote eelgrass growth. Using an excavator with high-precision global positioning system (GPS), a sand cap with an average thickness of 9.3±1.3 cm was placed on site. The following summer, divers successfully planted 80,000 eelgrass shoots on top of the sand-capped area. Observations indicated that the 80,000 planted shoots grew to approximately 860,000 shoots within one year.

Additional research has highlighted the potential benefits of covering seeds with a thin sand layer to improve germination rates. Infantes et al. (2016) found that seedling establishment rates increased by 2 to 6 times when seeds were covered with a 2 cm layer of sand, likely due to reduced predation and erosion as well as improved light availability. However, the burial depth of seeds remains critical, as studies have shown that germination success decreases significantly at depths beyond 5.5 cm (Greve et al., 2005; Jarvis and Moore, 2015). Optimal burial depths for seed establishment range from 2–4 cm, as noted in studies by Granger (2000), Jørgensen et al. (2019) and Marion and Orth (2010).

Combining insights from these studies, future restoration efforts should aim to optimise seed placement within the ideal depth range of 1–5.5 cm. By leveraging the dredging industry's expertise in hydraulic placement and sediment management, this integrated technique has the potential to enhance the scalability and success of seagrass restoration, ultimately contributing to the recovery and resilience of these vital marine ecosystems.

Settling behaviour of particles

In fluid dynamics, the settling velocity of particles is influenced by several factors, including grain size, shape, specific density and the properties of the surrounding fluid. For discrete particles of constant size, shape and weight, settling under gravity occurs until the drag force counterbalances the gravitational force, achieving a terminal settling velocity. In laminar flow conditions, characterised by a particle Reynolds number below 1, this velocity can be determined using Stokes' equation. Beyond this regime for higher velocities, empirical formulas, such as those proposed by Budryk (1936) and Ferguson and Church (2004), offer more accurate predictions, especially for irregularly shaped particles such as sand grains that deviate from perfect spheres.

While some research exists on the settling behaviour of high-density particles such as stones (e.g. Dietrich, 1982; Francalanci et al., 2021; Komar and Reimers, 1978), limited studies have explored the dynamics of ellipsoidal particles. This knowledge gap necessitated practical experiments to verify the settling behaviour of seagrass seeds, which differ significantly from the particles typically studied with a larger size, lower density and more natural variation.

In mixtures containing multiple particles, additional phenomena, such as hindered settling and density currents, influence particle behaviour. Stokes' formula for terminal settling applies to individual particles in stagnant fluid; however, in practice, particles interact dynamically. For a particle to descend, fluid upstream must move downward, creating space, which generates a small upward force affecting nearby particles. At higher concentrations, particles within close proximity (less than one particle diameter apart) enter each other's sphere of influence, leading to hindered settling. Consequently, when particle concentration surpasses a threshold, the mixture's settling velocity diminishes compared to the terminal velocity of individual particles.

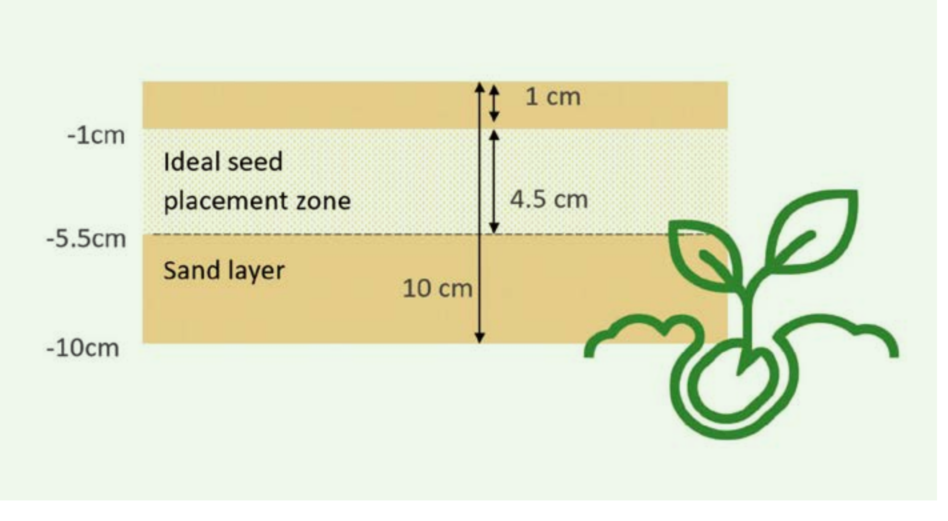


FIGURE 2

Diagram of ideal sediment cap with seagrass seeds.

A major challenge lies in the current unavailability of large-scale seed cultivation in nurseries.

From settling column experiments, Richardson and Zaki (1954) found a retardation factor applicable to Stokes settling equation for single-sized particle systems. In mixtures with varying particle types, such as seagrass seeds and sand grains, further adaptations are required. A common approach incorporates the volume fraction or concentration of each particle type to account for differences in density and size. In non-cohesive particle mixtures, settling velocities at low concentrations align with the terminal settling velocities of individual fractions. However, as volumetric concentration increases, hindered settling effects intensify, reducing the settling velocities of both fractions. The degree of reduction varies based on particle size, density and mixture concentration. Based on the formula from Mizra and Richardson (1979), larger particles such as seeds generate return currents that disproportionately affect the settling of smaller particles such as sands. The relative decrease in settling velocity of sand is expected to be higher than for seeds due to the return current of the larger particles influencing the finer particles more.

At sufficiently high densities, sediment mixtures may form a density current. Upon introduction into the water column, the mixture behaves as a denser collective body, settling as a unit before dispersing into individual particles. Additional factors, such as turbulent mixing introduce further complexity, which is challenging to quantify empirically with limited data.

To address these knowledge gaps, initial laboratory experiments investigated the settling behaviour of seagrass seeds by tracking their trajectories under controlled conditions. These experiments provide critical insights into the hydrodynamic interactions between seeds and sediment, laying the groundwork for optimising large-scale restoration techniques.

Experiments

Terminal settling velocity

The first experiment was set up to find the terminal settling velocity of the seeds and their variation based on size by releasing the particles into a graduated cylinder filled with saline water up to the 400 mm mark, maintaining a salinity of 32 parts per thousand (ppt) to prevent seed germination. A disk with a central gap was used to drop particles from the column's centre and then released by hand at the water surface. A LED screen provided an evenly distributed light source, enhancing the visibility of particle trajectories that was captured with a GoPro camera and later analysed.

Each seed was weighed and measured along three axes to investigate potential correlations with shape, size and density. Large natural variations in seed size and density were observed both within and between populations from Varna (Bulgaria), Voerså (Denmark) and Hamburger-Hallig (Germany). While no clear correlation between shape, density or settling velocity was established, these variations align with patterns reported in the literature. However, the accuracy of density measurements of individual seeds was limited by the precision of the scale, adding some uncertainty to the results.

The analysis of settling behaviour required not only determining terminal velocities but also tracking seed trajectories to assess horizontal movement and settling dynamics. A multi-step video analysis process was employed, including cropping, grayscale conversion and distortion correction. The trackpy package (Kim et al., 2018) was used to identify and follow individual seed trajectories, enabling precise calculations of average velocities. *Zostera marina*

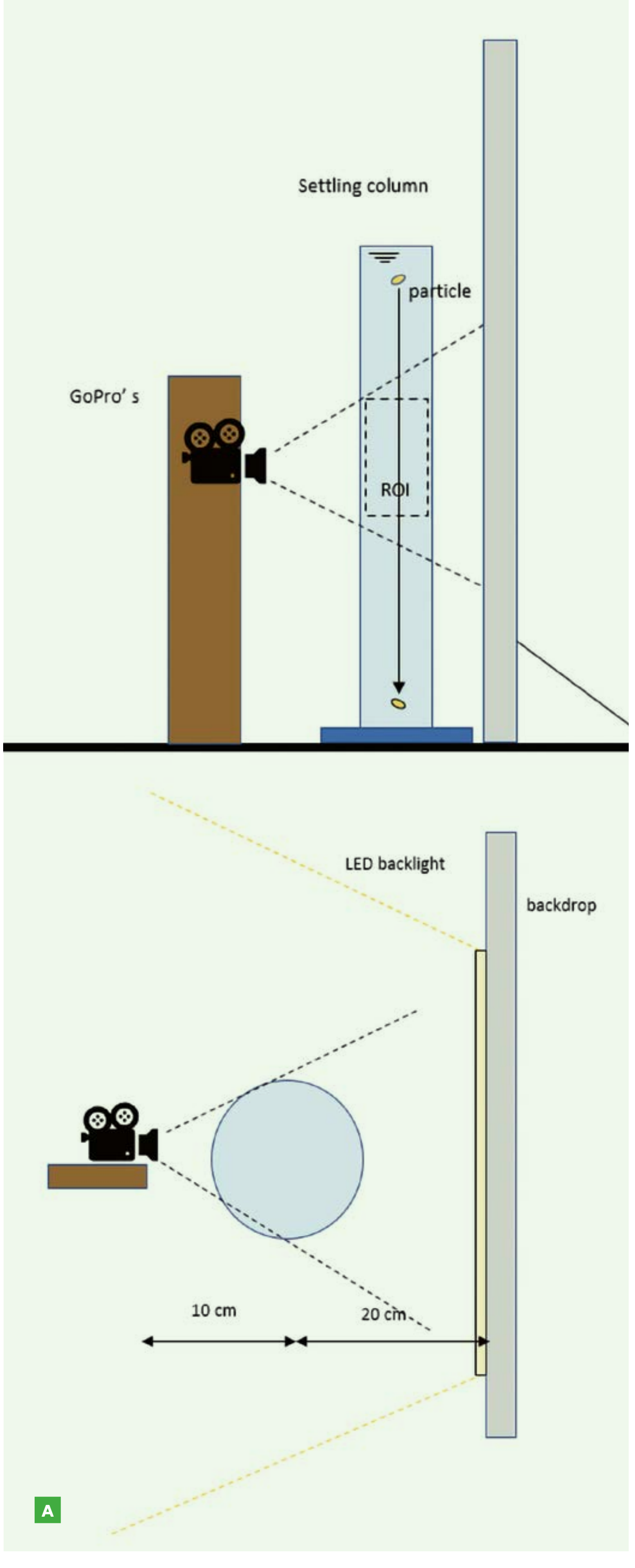


FIGURE 3

Schematic overview of setup for particle tracking (A) and photo of actual setup (B).

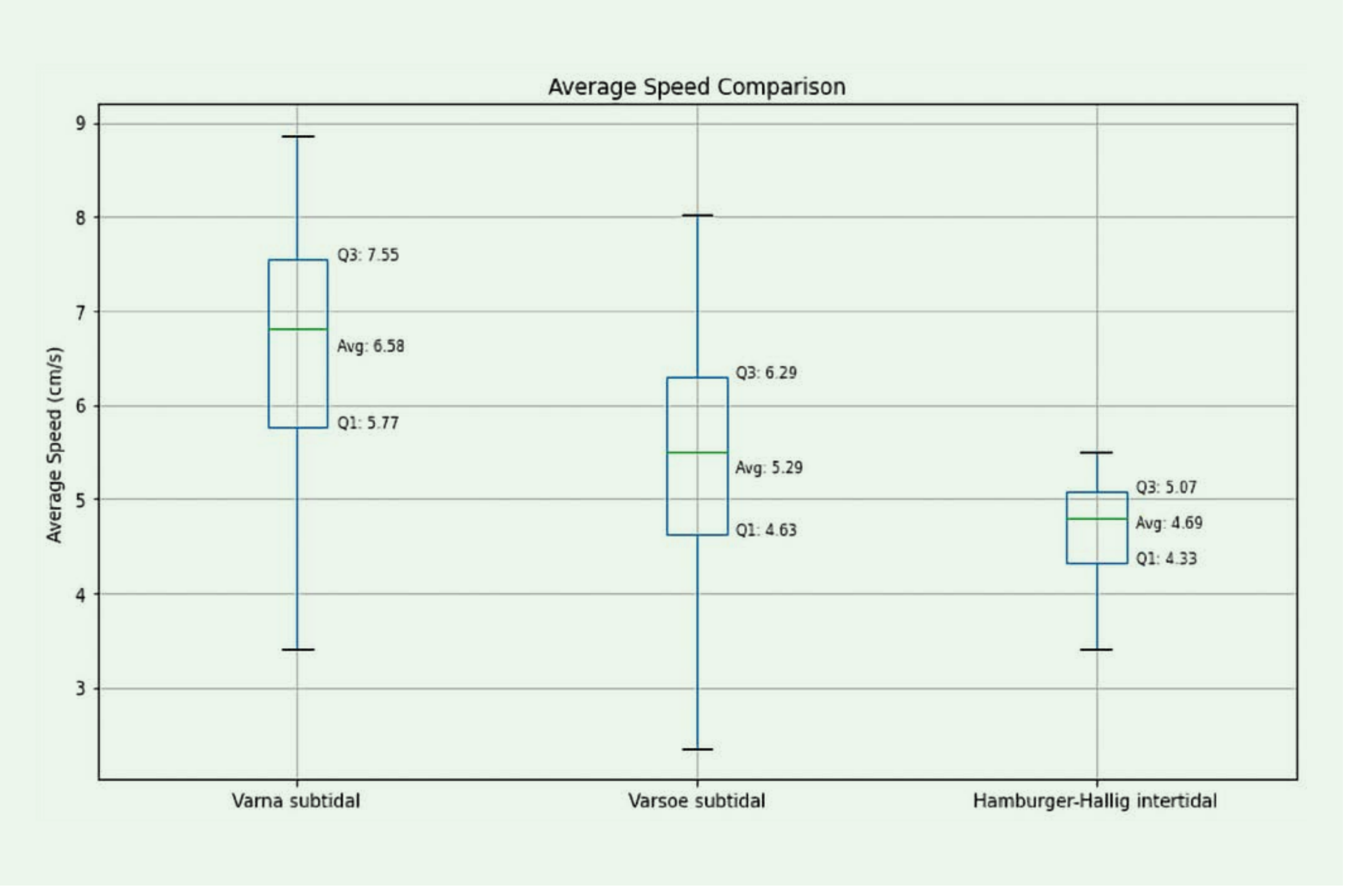


FIGURE 4

Spread in velocities of *Zostera marina* seeds from different locations.

seeds demonstrated an average settling velocity of 5.97 cm/s, with a standard deviation of 1.51 cm/s and a coefficient of variation (CV) of 0.252, reflecting substantial variability in the dataset.

Further analysis compared subtidal and intertidal *Zostera marina* seeds with seed mimics to explore their settling behaviour. Due to limited availability of *Zostera marina* seeds for experiments, several more commonly available seeds, i.e. clover, millet, alfalfa, cress have been studied for their shape and settling behaviour. Clover seeds, which shared a similar elliptical shape and most comparable mean settling velocity of 6.21 cm/s, were identified as the most suitable mimic for subtidal *Zostera marina* seeds, despite being slightly smaller in size. Using natural seeds also mimicked the natural variation of seeds found in seagrass seeds opposed to using nylon thread or 3D-printed particles that were also tested.

Subtidal seeds generally settled faster than their intertidal counterparts, with variations linked to differences in biotope conditions across the studied populations. This significant natural variability resulted in a broad distribution of settling velocities, highlighting the complexity of predicting seed behaviour in restoration efforts even with modification to formulas used for ellipsoidal particles.

Seed distribution

Various sediment concentrations (0.05, 0.1, 0.15, 0.2, 0.3) were used in the experiments. Initial tests utilised sieved mono-sized sand mixtures, including coarse, medium-coarse and fine sand. Based on the terminal settling velocity of the seed, the sediment mixture that has a similar velocity for medium-coarse sand (d=0.35mm), smaller velocity for fine sand (d=0.2mm) and larger settling velocity for coarser sand (d=0.43mm) were tested. The mixture tests were conducted using a transparent acrylate pipe, 120 cm in height and 10.5 cm in diameter, to observe the settling behaviour of seeds and sand in a confined space. The setup included a custom-designed 3D-printed plug for controlled sediment layer removal and a gate valve to maintain a vacuum and prevent air pockets. The entire assembly was placed on an elevated wooden table with a drainage system connected to a plastic tube and a ball valve for controlled water flow. It was possible to extend the setup with an additional piece of pipe and create a still water column below the ball valve in the second experiment. The two set ups are shown in Figure 5.

During every test approximately 100 seed mimics were used in each run to ensure consistency and control. In the first phase, the sediment was added in the pipe to achieve different concentration, then saline water with a salinity of 32 ppt was added and finally the mimics were introduced into the mixture. The column was manually mixed to achieve homogeneity and then allowed to

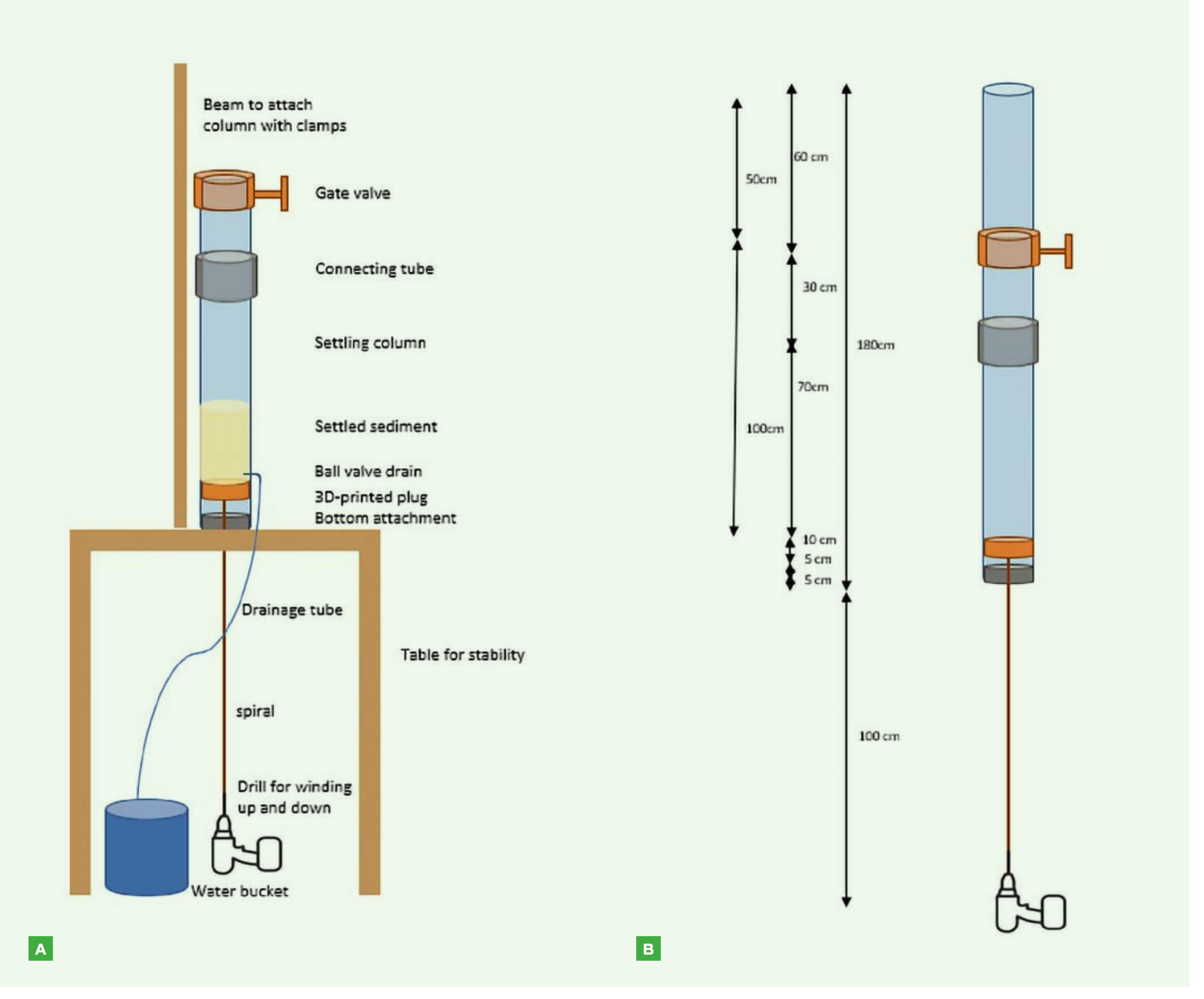


FIGURE 5

Experimental setup mixture test phase I (A) and phase II (B).

settle. The settled layer was pushed upward using a power tool and 1 cm slices were carefully sieved to count the number of seeds per layer.

In the second phase, a secondary pipe was added to introduce a mixture into the still water column, simulating a slurry being pumped into the water. The sediment-seed mixture was created on top of the water column and mixed using a paddle attached to a power tool. The suspended mixture was then released into the water column below by opening the valve with a raster printed beneath to prevent horizontal flows from the power tool as much as possible. The settled layer was analysed using the same methodology as in phase I.

Results

The initial hypothesis suggested that seeds and sand with similar settling velocities, particularly medium-coarse sand, would result in a more or less homogeneous distribution, with a slight segregation of the seeds to the bottom based on the hindered settling effect observed by Mirza and Richardson (1979). However, the results demonstrated a clear segregation effect, with seeds tending to accumulate in the upper layers of the sand mixture, especially at higher concentrations.

In phase I of the experiment, all seeds segregated to the top of the mixture, with the effect becoming more pronounced as seed concentration increased (see Figure 6). For medium-coarse and finer sand, seeds were distributed into lower layers, however a clear segregation effect persisted. This outcome contradicted the initial hypothesis. Due to the turbulence introduced by hand mixing the column, it was decided to test in phase II whether the same effect would occur under more realistic conditions by releasing the mixture into a still water column.

For medium-coarse sand (d_50=0.34 mm) at concentrations of 0.05 and 0.1, a significant portion of seeds settled in the ideal layer. However, at higher concentrations, most seeds accumulated above the ideal layer. Fine sand (d_50= 0.17 mm) similarly exhibited more seeds settling in the ideal and lower layers at lower concentrations, but segregation remained prominent at higher concentrations (above 0.2), with a substantial number of seeds ending at the top.

During phase II of the experiment, releasing a mixture by opening a gate valve for coarse sand (d_50=0.52 mm), the seeds segregated to the upper layer in the lower concentrations. In medium-coarse sand (d_50=0.34 mm), the seeds had similar settling velocities to the sand and resulted in a more homogeneous distribution as expected, however segregation still occurred, particularly at higher concentrations. For concentrations of 0.05 and 0.1 most of the seeds ended in the ideal layer. Fine sand (d_50= 0.17 mm) showed seeds distributed slightly lower in the layer, but segregation was still present at higher concentrations. These tests aligned better with the hypothesis yet still show the effect of hindered settling at higher concentrations, which was even more visible in phase I.

The study concluded that too coarse sand is unsuitable for seed distribution as it would not provide any benefit compared to hand-broadcasting to increase survival rate, as the seeds all end up in the top layer. While medium-coarse and fine sand showed better results at lower concentrations. Medium-

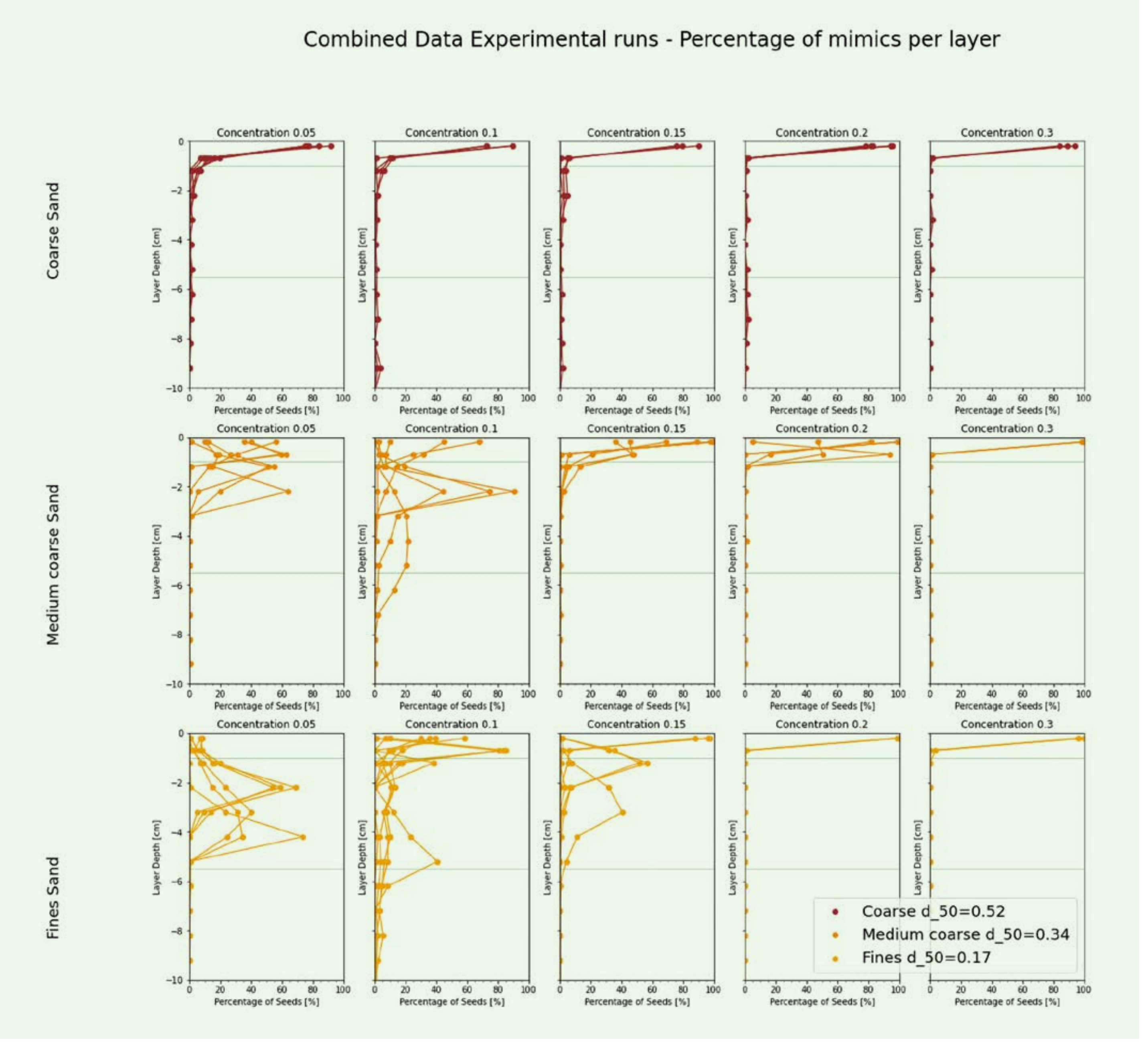


FIGURE 6

Results of where seed mimics end up in the settled layer for different types of sediment and concentration in mixture test phase I.

coarse sand would likely provide the most protection for the seeds and thus is the starting condition for further investigation of this new technique.

During the experiments, video analysis revealed a key observation: the dynamic behaviour of seeds differed significantly from that of the sand particles. While sand particles moved downward collectively, seeds exhibited rotational and hovering motions influenced by turbulence and return currents. This dynamic interaction contributed to the observed segregation effect, with seeds appearing to "hover" in place under certain conditions. Figure 8 provides a visual representation of these particle behaviours, highlighting the contrast between the steady downward motion of the sand and the complex rotational and turbulent motions of the seeds.

The findings suggest that the hindered settling effect and the dynamic behaviours of seeds are critical factors in determining the final distribution. Coarse sand is unsuitable for large-scale seed dispersal, while medium-coarse and fine sand show promise, particularly at lower concentrations. These insights are vital for refining techniques to optimise seagrass seed distribution in restoration projects.

Discussion

Seagrass restoration is crucial for coastal ecosystem management and seed-based methods offer promising potential for

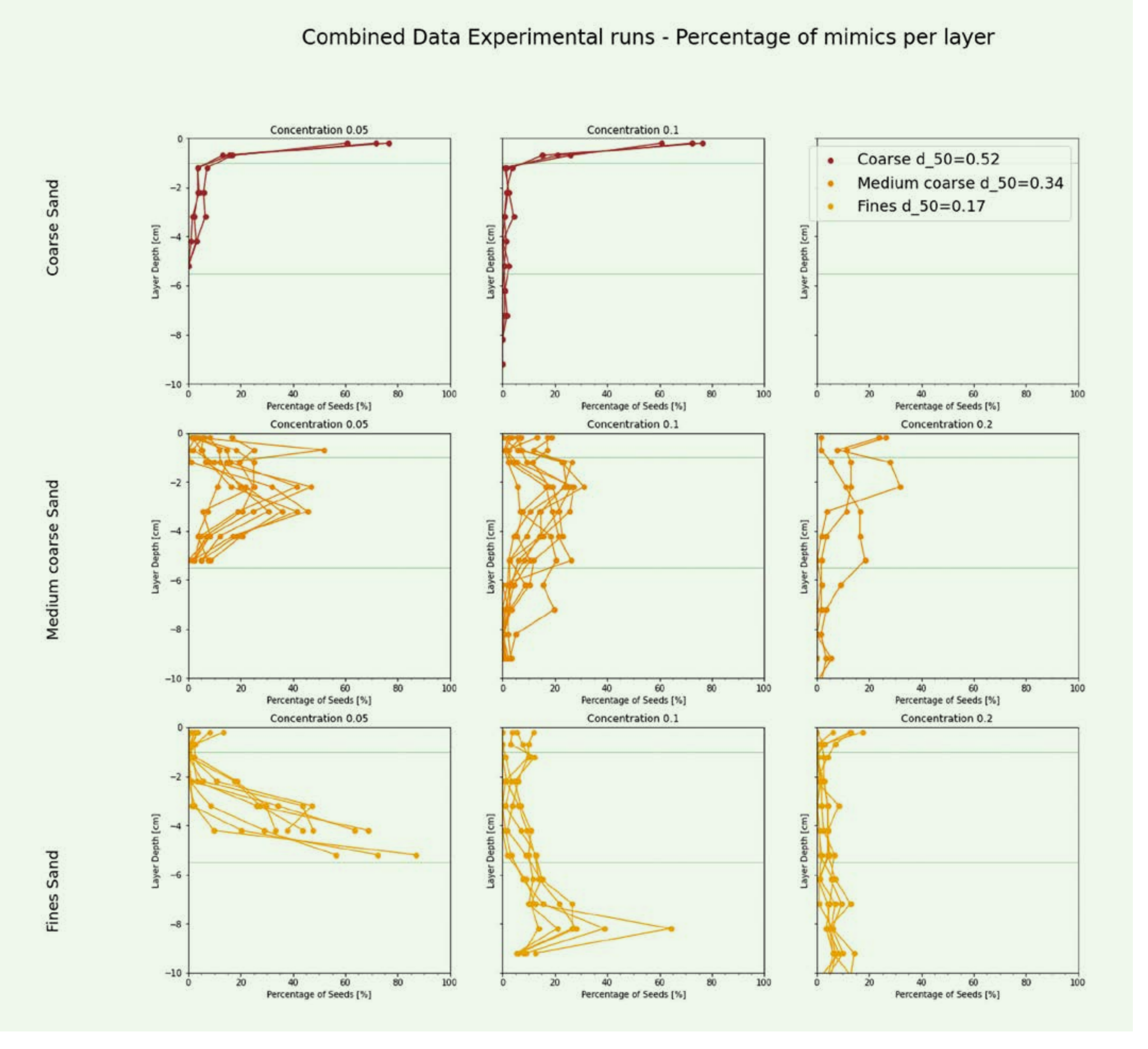


FIGURE 7

Overview of where seed mimics end up in the settled layer for different types of sediment and concentration in mixture test phase II.

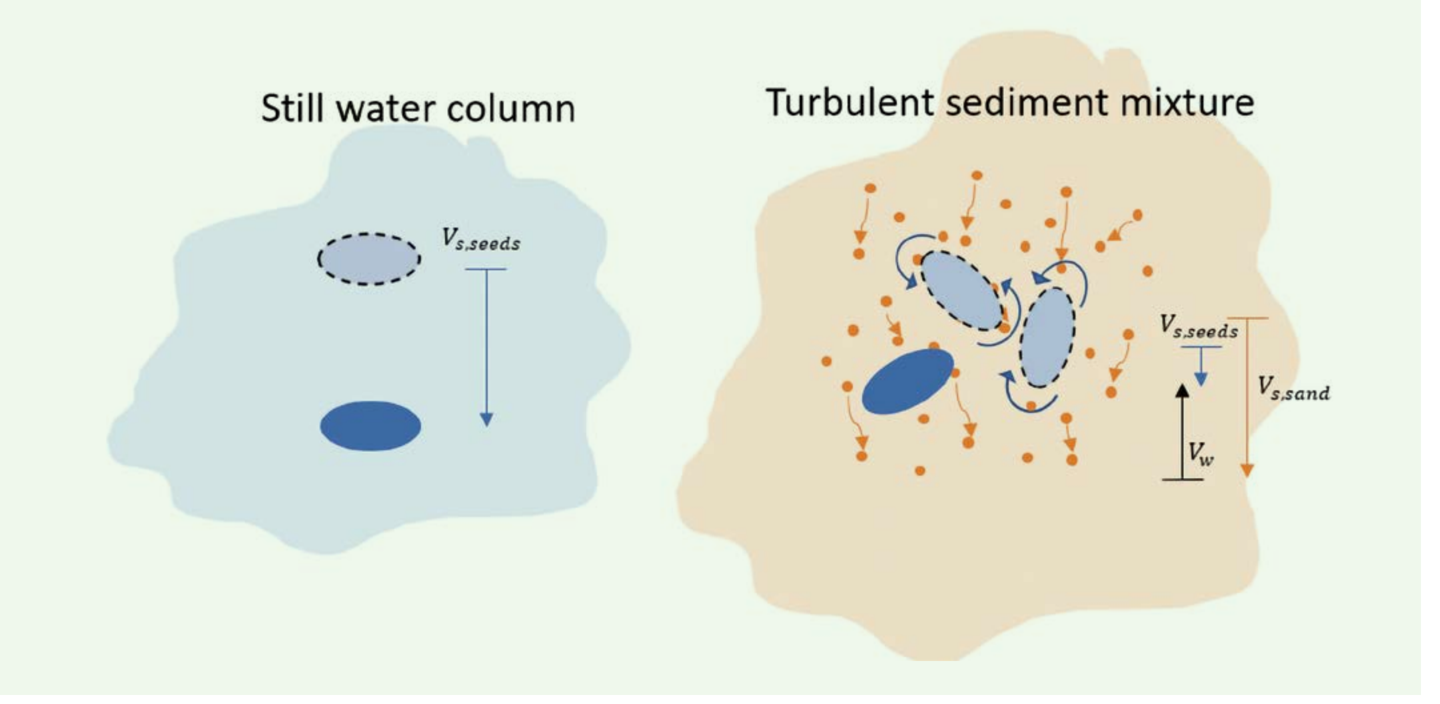


FIGURE 8

Visualisation difference in seed behaviour.

large-scale restoration efforts. An essential component of designing effective restoration techniques is understanding the settling behaviour of seagrass seeds, as this directly impacts their distribution and establishment. The study revealed significant variations in seed size and density, leading to a wide range of settling velocities. Seed mimics were used due to the scarcity of actual *Zostera marina* seeds, but this introduced complexities and differences, emphasising the need for cautious interpretation of results. While these seed mimics showed similarities in shape, size and settling velocities, minor differences in their settling paths were observed, such as increased horizontal movement and more drifting.

The initial hypothesis that seeds with similar settling velocities to sand particles would lead to a homogeneous distribution was not supported by the experimental results. Instead, seeds consistently segregated towards the upper layers, with this segregation effect becoming more pronounced at higher sand concentrations. This discrepancy suggests that the physical properties of the sediment mixture influence the settling behaviour of seagrass seeds differently from sand particles. The hindered settling effect, alongside the seeds' larger size and ellipsoidal shape, was identified as a likely cause for this behaviour. These factors resulted in seeds experiencing the sediment as a dynamic fluid medium with varying densities, which in turn led to significant rotational movement and less predictable settling dynamics compared to the sand particles. This highlights the need for further investigation into the complex interactions between seed morphology, sediment characteristics and settling behaviour in restoration settings.

In phase I of the experiment, which involved rotating a settling column, the hindered settling effect was effectively captured. However, this setup was also influenced by induced turbulence from the rotation and wall effects, which may have contributed to some inconsistencies in the data.
In contrast, phase II that simulated the pumping of a sediment mixture into still water produced different results due to additional factors, such as entrainment and initial seed velocities. These variations suggest that further refinement is needed to replicate real-world conditions more accurately. Additionally, material constraints such as the narrow grading of sand particles used in the experiments do not accurately reflect sediment mixtures available for large-scale execution. Future experiments should address these limitations and explore modifications that can enhance the accuracy and reliability of the method, including adjustments to sediment grading and experimental setups.

Further development

The ongoing research, which is part of a same programme with Van Oord, has shifted focus towards the practical application of these findings in the field. Moving away from fundamental behaviour analysis and concentrating on the methodology's rollout and implications for real-world seagrass restoration projects. In a laboratory, a scaled working model of a spreader pontoon was constructed to test the creation of thin sand

> **Coarse sand is unsuitable for large-scale seed dispersal, while medium-coarse and fine sand show promise.**

FIGURE 9

Location of trial using seed mimics (Scotland, November 2024).

layers with medium coarse sand at the suggested concentration of 0.05 and 0.1 with seed mimics. By sampling at various points, the seed distribution in each layer was compared to fundamental behaviour results, while varying water column heights, pumping speeds, etc.

Additionally, biological trials were conducted with the University of Groningen in the Netherlands to assess the germination rate of seeds in a sand-capped layer under different abrasion conditions caused by hydraulic pumping. With the obtained knowledge, a trail was executed using seed mimics in the cold month of November in preparation for the pilot with actual seed (see Figure 9). Future pilot tests are planned for April 2025 with *Zostera marina* seeds, marking an important step in evaluating the effectiveness of this approach in real-world conditions. This pilot will provide valuable insights into the operational feasibility of using sediment mixtures in large-scale seagrass restoration efforts and biological success rates when using this new method.

Conclusion

The study explored the potential of using traditional dredging techniques for seagrass restoration, focusing on the settling velocities of *Zostera marina* seeds and their distribution in sand-seed mixtures. The use of seed mimics due to the scarcity of actual seeds introduced complexities but provided valuable insights for large-scale restoration applications. The experiments demonstrated that seeds using low concentrations and medium-coarse to find sand would lead to the best distributions in a settled layer, increasing the survival rate of the sand. This behaviour was attributed to the hindered settling effect and the shape factor of the seeds, which caused them to experience the mixture as a fluid medium with different densities. The study highlighted the need for further research to understand the phenomena influencing seed distribution in sediment mixtures as it was different to the hypothesis based on fluid mechanics. Further research is needed to refine technique and understand the impact of various factors not yet examined, such as initial velocity, use of diffusers, less narrowly graded sand and other practical questions still to be further explored.

Acknowledgements

The authors extend their heartfelt gratitude to Dr. ir. Bram van Prooijen, the chair of this thesis, for his exceptional guidance, expertise and unwavering support throughout the research process. We also wish to express our deep appreciation to Jesper Elzinga, manager of the Environmental Department at Van Oord, for his continuous encouragement and leadership. Their contributions were instrumental to the success of this work, providing both inspiration and direction. Additionally, we would like to acknowledge the University of Groningen, under the supervision of Prof. Dr. Laura Grovers, for their significant partnership in the sand-capping seagrass restoration programme with Van Oord. The trails and seed collection in Scotland were made possible with help of our local partner Seawilding.

Summary

Seagrass restoration is crucial due to its benefits for coastal protection, carbon sequestration and biodiversity enhancement. Traditional planting methods, which involve manually planting seagrass shoots, are labour-intensive and challenging to scale. This research explored the initial steps to a seed-based restoration approach, which could be more scalable and cost-effective.

The study focuses on the fluid mechanics and behaviour of seagrass seeds (*Zostera marina*) in sand mixtures. Laboratory experiments were conducted to determine the best sediment concentration and grain sizes to achieve optimal depth for seed placement, which was found to be between 1-5.5 cm based on previous research. The experiments used seed mimics to simulate the behaviour of actual seagrass seeds, given their scarcity. The average terminal settling velocity of the seeds was measured at 5.97 cm/s, slightly higher, comparable and smaller than that of sand particles of the different mixtures.

Various sediment-water mixtures were tested, revealing that seeds tend to segregate to the top of the settled sand layer, especially in mixtures with larger grain sizes and higher sediment concentrations. The best results were obtained with low sediment concentrations of 0.05-0.1 and fine to medium coarse grain sizes, where the majority of seeds settled at the optimal depth.

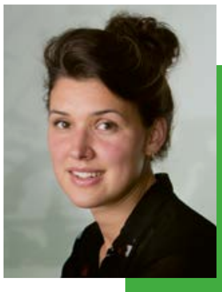
The findings provide valuable insights into the dynamics of seed segregation in sediment mixtures, highlighting the potential for using seed-based methods in large-scale seagrass restoration projects using conventional dredging techniques.

Anne-May Alkemade

Anne-May works as an environmental engineer at Van Oord Dredging & Marine Contractors in Rotterdam. She graduated (2024) from Delft University of Technology in the Netherlands with a specialisation in Hydraulic Engineering. Her thesis, titled "Seed-sediment dynamics: An experimental study into the behaviour of seagrass seeds in sediment mixtures," earned her the *Waterbouwprijs* (Hydraulic Engineering Award) 2024 for which she was invited to write this article.

Dr. ir. Rudy Helmons

Rudy is an associate professor in Offshore and Dredging Engineering at the Department of Maritime and Transport Technology, Delft University of Technology. His research focuses on physical processes related to dredging and seabed mining, including mechanical and hydraulic excavation, hydraulic transport and sediment dynamics. He has been involved in several deep-sea mining projects and has a solid background in mechanical engineering and fluid mechanics. Rudy served as the second supervisor for the thesis work from Delft University of Technology.



Marlies van Miltenburg

Marlies holds an MSc in Environmental Fluid Mechanics from Delft University of Technology (2017). She has been with Van Oord's Environmental Engineering Department for over six years, leading projects such as sediment spill management for the Fehmarnbelt tunnel dredging in Denmark and has worked on various tenders and projects with a focus on ESG due diligence, ESIA guidance and turbidity monitoring. Marlies is now part of the engineering manager's pool. She served as company supervisor during the thesis work.

Roosmarijn van Zummeren

Roosmarijn has been working as an ecologist at Van Oord Dredging & Marine Contractors for 5 years, focusing on mitigating impacts on marine ecosystems, especially seagrass. She has led various projects related to coral and seagrass rehabilitation and environmental management. Roosmarijn holds a master's degree in marine sciences from Utrecht University in the Netherlands, where she focused on marine biogeochemistry. She leads the development of seagrass restoration methods within Van Oord, with an upcoming pilot project scheduled in Scotland in March 2025.

References

Bayraktarov E., Saunders M.I., Abdullah S., Mills M., Beher J., Possingham H.P., Mumby P. J. and Lovelock C.E. (2016)
The cost and feasibility of marine coastal restoration. *Ecological Applications, 26*(4), 1055-1074. https://doi.org/10.1890/15-1077

Budryk W. (1936)
Contribution à la théorie du lavage. *Revue de L'Industrie Minérale*, 374.

Dietrich W.E. (1982)
Settling velocity of natural particles. *Water Resources Research, 18* (6), 1615-1626. https://doi.org/10.1029/WR018i006p01615

Duarte C.M. and Krause-Jensen D. (2017)
Export from seagrass meadows contributes to marine carbon sequestration. *Frontiers in Marine Science, 4*(JAN), 217090. https://doi.org/10.3389/FMARS.2017.00013

Ferguson R.I. and Church M. (2004)
A Simple Universal Equation for Grain Settling Velocity. *Journal of Sedimentary Research, 74*(6), 933-937. https://doi.org/10.1306/051204740933

Flindt M.R., Oncken N.S., Kuusemäe K., Lange T., Aaskoven N., Winter S., Sousa A.I., Rasmussen E.K., Canal-Verges P., Connolly R.M. and Kristensen E. (2022)
Sand-capping stabilizes muddy sediment and improves benthic light conditions in eutrophic estuaries: Laboratory verification and the potential for recovery of eelgrass (*Zostera marina*). *Journal of Sea Research*, 181, 102177. https://doi.org/10.1016/J.SEARES.2022.102177

Francalanci S., Paris E. and Solari L. (2021)
On the prediction of settling velocity for plastic particles of different shapes. *Environmental Pollution, 290*, 118068. https://doi.org/10.1016/J.ENVPOL.2021.118068

Govers L.L., Heusinkveld J.H.T., Gräfnings M.L.E., Smeele Q. and van der Heide T. (2022)
Adaptive intertidal seed-based seagrass restoration in the Dutch Wadden Sea. *PLOS ONE, 17*(2), e0262845. https://doi.org/10.1371/JOURNAL.PONE.0262845

Gräfnings M.L.E., Heusinkveld J.H.T., Hoeijmakers D.J.J., Smeele Q., Wiersema H., Zwarts M., van der Heide T. and Govers L L. (2023)
Optimizing seed injection as a seagrass restoration method. *Restoration Ecology, 31*(3), e13851. https://doi.org/10.1111/REC.13851

Granger S., Traber M.S. and Nixon S.W. (2000)
The influence of planting depth and density on germination and development of *Zostera marina* L. seeds. *Biologia Marina Mediterranea, 7* (3), 55–58.

Greve T.M., Krause-Jensen D., Rasmussen M.B. and Christensen P.B. (2005)
Means of rapid eelgrass (*Zostera marina* L.) recolonisation in former dieback areas. *Aquatic Botany, 82*(2), 143-156. https://doi.org/10.1016/J.AQUABOT.2005.03.004

Hansen J. and Reidenbach M. (2012)
Wave and tidally driven flows in eelgrass beds and their effect on sediment suspension. *Marine Ecology Progress Series, 448*, 271-287. https://doi.org/10.3354/meps09225

Infantes E. (2021)
Sand capping to promote eelgrass restoration. https://www.eduardoinfantes.com/sand-capping-eelgrass-restoration/

Infantes E., Eriander L. and Moksnes P. (2016)
Eelgrass (*Zostera marina*) restoration on the west coast of Sweden using seeds. *Marine Ecology Progress Series, 546*, 31-45. https://doi.org/10.3354/meps11615

Infantes E., Hoeks S., Adams M.P., van der Heide T., van Katwijk M.M. and Bouma T.J. (2022)
Seagrass roots strongly reduce cliff erosion rates in sandy sediments. *Marine Ecology Progress Series, 700*, 1-12. https://doi.org/10.3354/MEPS14196

Jarvis J.C. and Moore K.A. (2015)
Effects of seed source, sediment type, and burial depth on mixed-annual and perennial *Zostera marina* L. seed germination and seedling establishment. *Estuaries and Coasts, 38*(3), 964-978.https://doi.org/10.1007/S12237-014-9869-3

Jørgensen M.S., Labouriau R. and Olesen B. (2019)
Seed size and burial depth influence *Zostera marina* L. (eelgrass) seed survival, seedling emergence and initial seedling biomass development. *PLOS ONE, 14*(4), e0215157. https://doi.org/10.1371/JOURNAL.PONE.0215157

Kilminster K., McMahon K., Waycott M., Kendrick G.A., Scanes P., McKenzie L., O'Brien K.R., Lyons M., Ferguson A., Maxwell P., Glasby T. and Udy J. (2015)
Unravelling complexity in seagrass systems for management: Australia as a microcosm. *Science of The Total Environment, 534*, 97-109. https://doi.org/10.1016/J.SCITOTENV.2015.04.061

Kim D., Son Y. and Park J. (2018)
Prediction of settling velocity of nonspherical soil particles using digital image processing. *Advances in Civil Engineering, 2018*(1), 4647675. https://doi.org/10.1155/2018/4647675

Komar P.D. and Reimers C.E. (1978)
Grain shape effects on settling rates. *The Journal of Geology, 86*(2), 193-209. https://doi.org/10.1086/649674

Marion, S.R. and Orth R.J. (2008)
Innovative techniques for large-scale seagrass restoration using *Zostera marina* (eelgrass) seeds. *Restoration Ecology, 18*(4), 514–526. https://doi.org/10.1111/j.1526-100X.2010.00692.x

Marion S.R. and Orth R.J. (2010)
Innovative techniques for large-scale seagrass restoration using Zostera marina (eelgrass) seeds. https://doi.org/10.1111/j.1526-100X.2010.00692.x

Mirza S. and Richardson J.F. (1979)
Sedimentation of suspensions of particles of two or more sizes. *Chemical Engineering Science, 34*(4), 447–454. https://doi.org/10.1016/0009-2509(79)85088-5

Mtwana Nordlund L., Koch E.W., Barbier E.B. and Creed J.C. (2016)
Seagrass ecosystem services and their variability across genera and geographical regions. *PLOS ONE, 11*(10), e0163091. https://doi.org/10.1371/JOURNAL.PONE.0163091

Oncken N.S., Lange T., Kristensen E., Quintana C.O., Steinfurth R.C. and Flindt M.R. (2022)
Sand-capping – A large-scale approach to restore organic-enriched estuarine sediments. *Marine Environmental Research, 173*, 105534. https://doi.org/10.1016/j.marenvres.2021.105534

Richardson J.F. and Zaki W.N. (1954)
The sedimentation of a suspension of uniform spheres under conditions of viscous flow. *Chemical Engineering Science, 3*(2), 65-73. https://doi.org/10.1016/0009-2509(54)85015-9

Richardson J.F. and Zaki W.N. (1954)
Sedimentation and fluidisation. *Trans. Inst. Chem. Eng., 32*(4).

Short F., Carruthers T., Dennison W. and Waycott M. (2007)
Global seagrass distribution and diversity: A bioregional model. *Journal of Experimental Marine Biology and Ecology, 350*(1-2), 3-20. https://doi.org/10.1016/j.jembe.2007.06.012

Unsworth R.K.F., Bertelli C.M., Cullen-Unsworth L.C., Esteban N., Jones B.L., Lilley R., Lowe C., Nuuttila H.K. and Rees S.C. (2019)
Sowing the seeds of seagrass recovery using hessian bags. *Frontiers in Ecology and Evolution, 7.* https://doi.org/10.3389/fevo.2019.00311

van der Heide T., van Nes E.H., van Katwijk M.M., Olff H. and Smolders A.J P. (2011)
Positive feedbacks in seagrass ecosystems – Evidence from large-scale empirical data. *PLOS ONE, 6*(1), e16504. https://doi.org/10.1371/JOURNAL.PONE.0016504

van Katwijk M.M., Thorhaug A., Marbà N., Orth R.J., Duarte C.M., Kendrick G.A., Althuizen I.H.J., Balestri E., Bernard G., Cambridge M.L., Cunha A., Durance C., Giesen W., Han Q., Hosokawa S., Kiswara W., Komatsu T., Lardicci C., Lee K., … Verduin J.J. (2016)
Global analysis of seagrass restoration: the importance of largescale planting. *Journal of Applied Ecology, 53*(2), 567–578. https://doi.org/10.1111/1365-2664.12562

Waycott M., Duarte C.M., Carruthers T.J.B., Orth R.J., Dennison W.C., Olyarnik S., Calladine A., Fourqurean J.W., Heck K.L., Hughes A.R., Kendrick G.A., Kenworthy W.J., Short F.T. and Williams S.L. (2009)
Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *Proceedings of the National Academy of Sciences of the United States of America, 106*(30), 12377-12381. https://doi.org/10.1073/PNAS

Photo © Seaboost

ARTIFICIAL REEFS IN THE UAE COASTLINE: A SUSTAINABLE SOLUTION FOR MARINE BIO-DIVERSITY

Dredging and reclamation projects have played an important role in the UAE's rapid development, meanwhile efforts are continuously made to balance progress with marine ecosystem conservation. This paper explores the development of fish domes and 3D-printed artificial reefs, highlighting their role in providing marine habitats, promoting biodiversity and supporting sustainable development. Case studies from Abu Dhabi region demonstrate the effectiveness in restoring marine environment. By integrating innovative reef structures with sustainability goals, the UAE ensures that economic growth aligns with environmental conservation, fostering a resilient marine ecosystem for future generations.

History

The United Arab Emirates (UAE), established as a Federation of seven emirates in December 1971, is a desert dominated country with a relatively limited landmass. The country emerged against the backdrop of poverty and socio-economic underdevelopment. With a population of no more than 180,000 inhabitants in 1968, the UAE's economy was largely shaped by subsistence activities, including agriculture, pearling, fishing and trading.

In the late 1960s, infrastructure was nearly non-existent. Yet, within 53 years the UAE was able to evolve from a subsistence economy into a country with one of the most competitive and advanced economies in the world in terms of business regulations, infrastructure and technological advancement. The long-term government initiative, UAE Centennial 2071, holds a key emphasis on reducing reliance on oil through diversification.

The country also achieved record-breaking growth rates having 10.6 million inhabitants as of 2023 with a projected increase of 44% to 15.4 million by 2050. Thus, the UAE's vision and ambition for the future are deeply intertwined with its reliance on dredging and reclamation projects, as they are integral to the country's broader economic, environmental, and infrastructural goals.

Dredging and reclamation in the UAE

The UAE's vision focuses on sustainability, diversification, innovation, and global leadership, and dredging projects play a crucial role in realising these objectives. Dredging and reclamation are carried out for expanding and enhancing land use in coastal and waterfront areas, supporting urban development, infrastructure projects and environmental restoration. Dredging helps deepen and widen waterways, facilitating better shipping routes, ports and flood control, while reclamation creates new land for construction, agriculture and recreation. These processes are crucial for UAE since the country is with limited natural land availability.

Once a desert landscape, the country has transformed with towering skyscrapers, extensive infrastructure and high-tech industries, Figure 1 and Figure 2 show the drastic changes of Abu Dhabi and Dubai's coastline. Reclamation has been key to this development, particularly in creating land for infrastructure projects, such as airports, ports, residential complexes and tourism destinations like Palm Jumeirah.

Importance of marine environment restoration

While dredging and reclamation efforts have played a critical role in expanding the UAE's urban and industrial landscape, the successes of these projects must also be viewed in the context of broader environmental considerations. As the country develops its infrastructure and land resources, it is equally important to focus on the restoration of its marine environment. NMDC Dredging & Marine, founded as National Marine Dredging Company in 1976, takes it upon itself to contribute to the country's vision. In addition to undertaking major dredging and reclamation projects, NMDC D&M is committed to implementing

FIGURE 1

Abu Dhabi region in 1984 (A) and 2025 (B). Source: Google Earth.

FIGURE 2

Dubai's coastline in 1984 (A) and 2025 (B). Source: Google Earth.

> Once a desert landscape, the country has transformed with extensive infrastructure.

sustainable practices in all operations of its business units.

In all practices carried out by NMDC, the global sustainability goals are upheld to ensure environmental protection, social equity and economic growth, contributing to a sustainable future. These sustainable practices involve short- and long-term initiatives, such as:

- water quality monitoring;
- sediment management;
- sustainable fuel use;
- habitat restorations;
- Environmental Impact Assessments (EIAs);
- local employment and training programmes; and
- research and development.

Marine ecosystems provide essential services, such as carbon sequestration, coastal protection and biodiversity, which are vital for maintaining ecological balance and supporting local communities. By integrating marine environment rehabilitation into the UAE's broader vision of sustainability, the country can ensure that its growth is both economically beneficial and environmentally responsible.

Dredging can cause disturbance to natural habitats, including coral reefs, seagrass beds and coastal wetlands. These ecosystems are vital to marine life as they provide food, shelter and breeding grounds for countless species. For example, coral reefs take thousands of years to form. With growth rates of 0.3 to 2 cm per year for massive corals, and up to 10 cm per year for branching corals, it can take up to 10,000 years for a coral reef to reach maturity. Their fragile balance can be easily disturbed by sedimentation, pollution and physical damage, leading to long-term ecological degradation.

Given the slow rate at which natural reefs form and their importance to marine biodiversity, restoring these environments is

FIGURE 3

Fish domes installed at different project locations in Abu Dhabi region.

vital. Artificial reefs, made from materials like concrete or other durable structures, help promote marine life by providing surfaces for coral growth and shelter for fish, mimicking the role of natural reefs. These efforts can help rebuild marine biodiversity and ecosystem services, creating a buffer for the ecosystems that dredging often threatens.

Fish dome projects in Abu Dhabi region

Project goals and objectives

In the past decade, several projects have been conducted with the following initiatives:

1. Marine habitat restoration: To create new habitats for marine life, including fish and corals, through the construction of man-made fish domes. The aim is to provide a safe refuge for fish to avoid predators and offer an ideal environment for their growth.
2. Fish attraction: One primary goal is to restore fish populations in areas impacted by offshore construction. The fish domes offer shelter for various species, promote coral growth and support the return of fish by providing a safe environment for reproduction. The long-lasting design also encourages coral blooms, helping to restore balance in ecosystems affected by dredging and reclamation activities.
3. Long-term sustainability: The project aims to enhance marine health by fostering the growth of fish populations and coral reefs. By creating stable habitats, marine ecosystems are restored, promoting long-term sustainability. These efforts will ensure the development of a resilient underwater environment, benefiting marine life for future generations.

LOCATION	YEAR	TYPE A	TYPE B	TYPE C	TYPE D	TYPE E	TYPE F	TOTAL
		Dome	Steel Pipe	Concrete Pipe	Concrete Box	Triangular Concrete	Colony Reef	
Sir Bani Yas Island	2023				3,998			**3,998**
Umm Al Nar - 1	2023	75	75		543	74		**767**
Umm Al Nar - 2	2021	30	866					**896**
Al Reem Island - 1	2021		30					**30**
Al Reem Island - 2	2023		32					**32**
Ras Al Mohsana	2023	648	648	1,296	648	648	17	**3,905**
Ramhan Island	2024				5			**9,628**

TABLE 1

Number of different dome types installed in different locations.

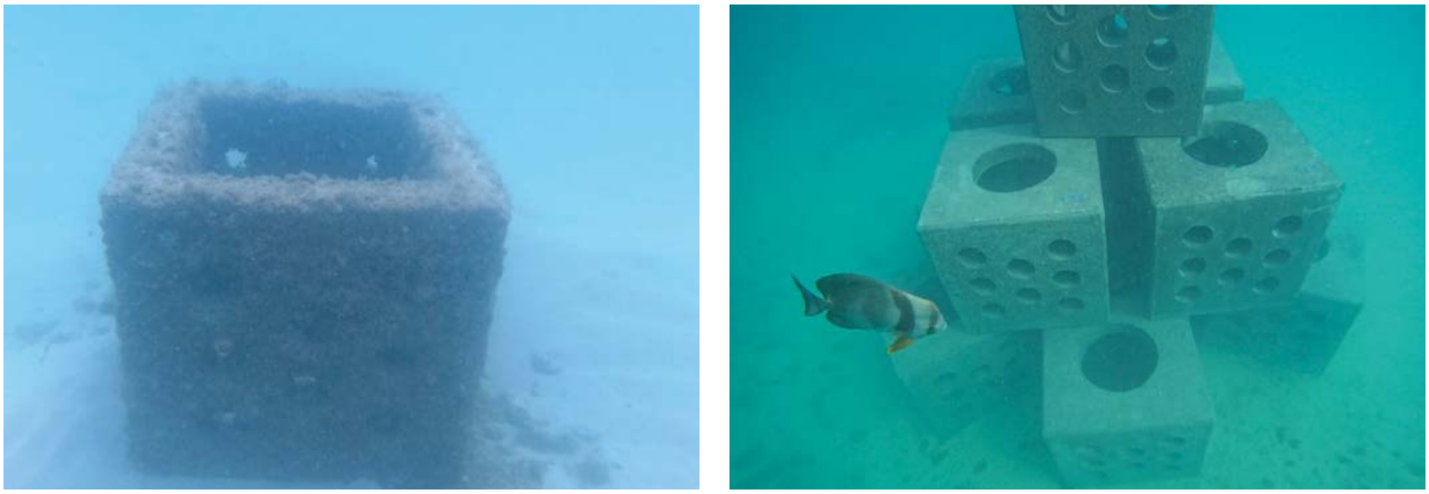


FIGURE 4

Type D fish domes: concrete boxes.

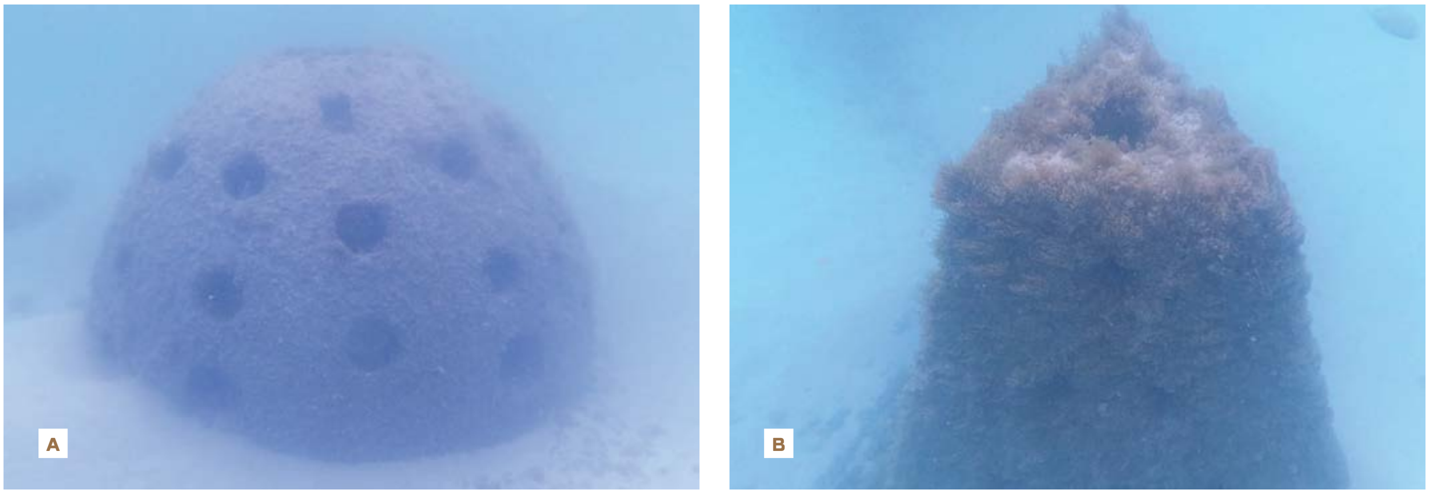


FIGURE 5

Type A fish dome: dome shaped (A) and type E fish dome: triangular concrete (B).

Overview of fish dome installations

Figure 3 illustrates the locations of various fish dome projects completed in Abu Dhabi region, UAE. While Table 1 provides an overview on the number of different types of fish domes used in each location.

Together with our project partners, NMDC follows several phases for each project.

Engineering phase

Scientific and mathematical principles are used to design and implement solutions in the safest and most economical way. The design of the shapes of reinforced concrete fish domes are inspired by nature. Although it is difficult to create exact replicas of natural shapes, the goal is to choose designs that are easy to manufacture and provide structural stability. These shapes provide the best support for marine life, while at the same time enabling designs to be produced economically and more easily.

Execution phase

During the execution of these projects, typically one month is required for the fabrication, quality control, storage, maintenance, transportation and underwater installation of one reinforced concrete fish dome. Considering the project scope, duration and demands, the necessary arrangements are made at the production site to ensure efficient mass production of concrete elements. The number of fish domes to be installed in the project determines the timeline. Weather conditions at sea are also considered when planning the installation time, as this is essential for safe and effective underwater installation.

Research and development phase

As the project continues, marine biologists are brought in to observe which types of fish domes work best in different marine project locations (see Figures 4 and 5). These studies help in understanding the needs of various fish species and other marine life and provide guidance on which dome designs are most effective. In this way, engineering principles are combined with natural inspiration and scientific research to develop the most effective, durable and economical solutions for each project.

FIGURE 6

Traditional fish habitat design.

The effect of fish domes on marine environment

These reinforced concrete fish domes are placed in designated project areas in order to reduce the environmental impact of offshore dredging and construction activities. The artificial fish domes are manufactured and installed to create and restore new habitats in areas where natural habitats have been disturbed or damaged. By installing these structures at sea, the project site attracts different species of fish back to the area, which benefits the overall health of the marine ecosystem. It has been witnessed that fish domes help restore biodiversity and create a more balanced environment for marine life.

It should be mentioned that these areas where fish domes are installed are protected areas where commercial fishing activities are not allowed. These protected areas provide a safe haven for marine life without the pressure of human activities, allowing underwater ecosystems to recover and develop.

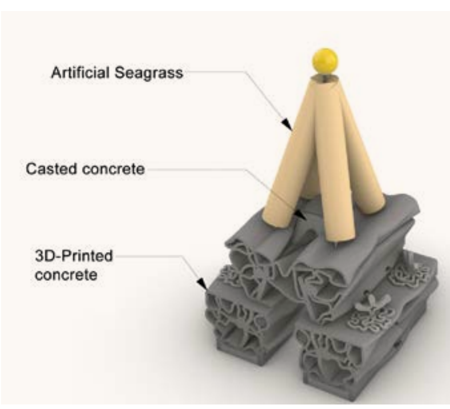
In addition, fish domes not only contain fish and corals but also other crustaceans, such as crabs and shrimps. These small creatures are a source of food for other larger creatures, which supports the formation of the food chain. The fish domes help creatures affected by dredging to return to their habitats.

Through these projects, marine life and ocean ecosystems are protected, creating sustainable environments that will support marine life for future generations.

3D-printed artificial reefs

Artificial reef design evolution

There has been relatively little development in the science behind artificial reef design since the Greeks and Romans started placing stones, pottery and other objects to attract fish into fishing areas. In more recent times, ships, trains, tyres, blocks and many other types of unwanted objects have been dumped to provide subsea habitats for marine life.



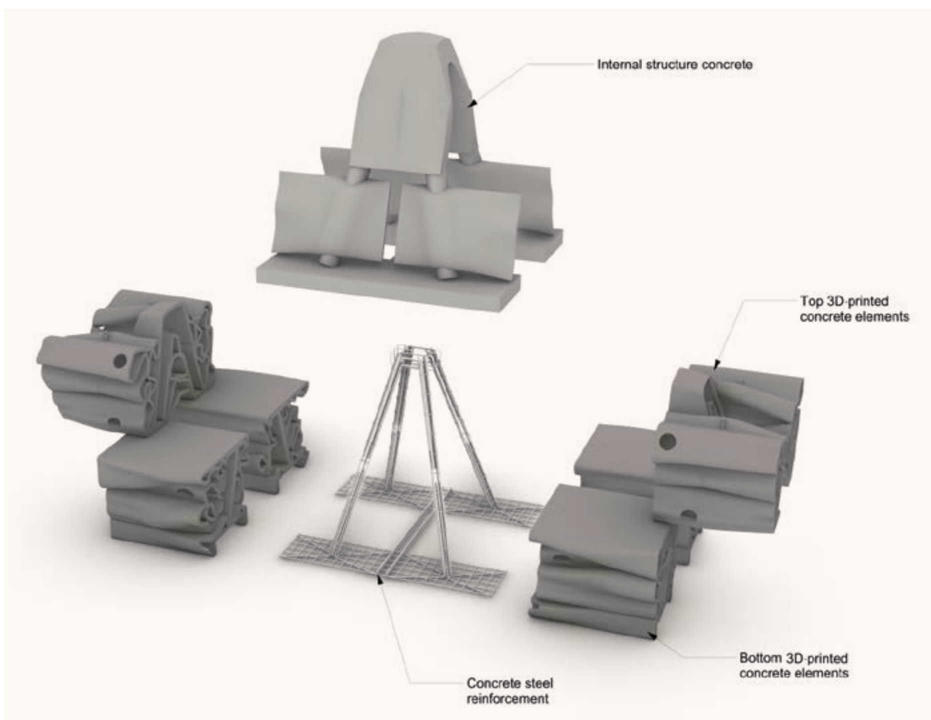
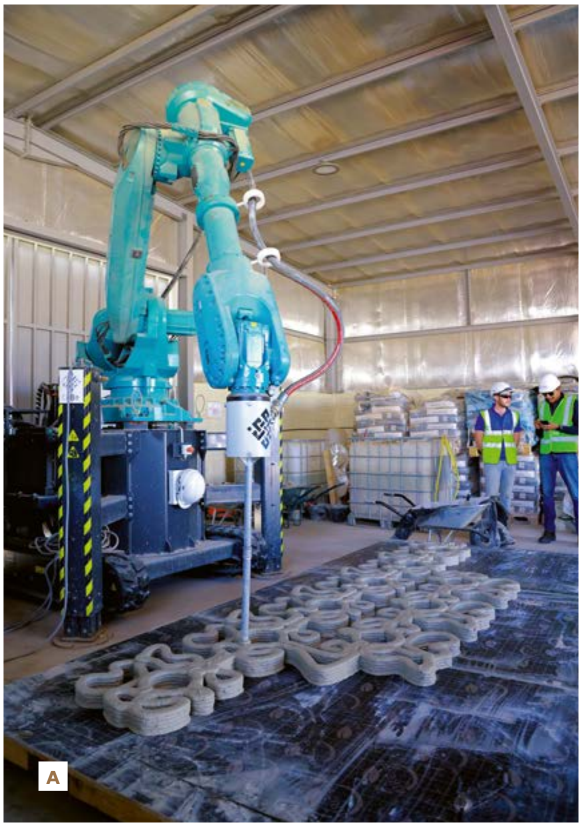


FIGURE 7

Computer model of 3D-printed reef. Image courtesy of Seaboost.



A

B

FIGURE 8

3D printing machine (A) and assembled reef unit (B).

The traditional artificial reef or fish habitat design comprises of low complexity precast concrete shells of various shapes and sizes. Some typical designs are shown in Figure 6.

Today with advances in 3D printing technologies, we can make highly complex artificial reef designs that are tailored to the marine life and engineered to support biodiversity. High complexity is desirable to more effectively mimic the characteristics of the natural marine environment. Numerous cavities can be created where the apertures, length, shape and orientation to the current are be tailored to target species. Typically, the traditional fish habitat only has one large cavity per unit. Figure 7 shows the computer model for the 3D-printed reef design being implemented for the proposed pilot project.

Comparison of the environmental benefits

3D-printed reefs are far superior to the traditional fish habitats. The large number of small closed ended cavities provide a much better habitat for juvenile and pre-adult fish communities. The 3D-printed reefs, in addition to providing shelter, are therefore more effective as a fish nursery, which helps support population growth not just attracting existing fish already in the area. Non-customised reefs can function as ecological traps, where the reefs inadvertently attract marine organisms to settle and thrive in areas that are ultimately detrimental to their survival and reproduction, leading to negative impacts on their overall fitness and survival (Komyakova et al., 2021).

Another environmental benefit of the 3D-printed reef design over traditional design is its ability to create enclosed cavities of varying shapes and sizes, providing separate habitats for different species across multiple trophic levels within a single reef unit. This means that species from different levels of the food chain can coexist within the same unit. Invertebrate species that typically like to hide in holes and crevices also benefit more from the more numerous cavities of different shapes and sizes.

Due to the additive concrete 3D printing process, the reef unit has a more complex, grooved and undulating surface. Together with the semi-porous texture, this makes it a suitable substrate for colonisation by corals and fixed species. Traditional artificial reefs tend to have smooth form finishes, which is not favourable to colonisation by fixed species. Not only this but the 3D-printed reefs have significantly more colonisable surface area to the traditional reefs of comparable size or weight.

3D-printed reefs offer remarkable customisation capabilities, allowing for adaptive shapes that can be tailored to the specific needs of local marine species. Additionally, the shape and complexity of the 3D-printed reefs can be adapted based on environmental conditions, such as water flow and sedimentation patterns, as well as to the location, if space is limited or if reefs need to occupy a specifically shaped area.

When considering the environmental impact from the manufacturing and installation process, 3D-printed reefs require less cement and concrete materials and since they provide

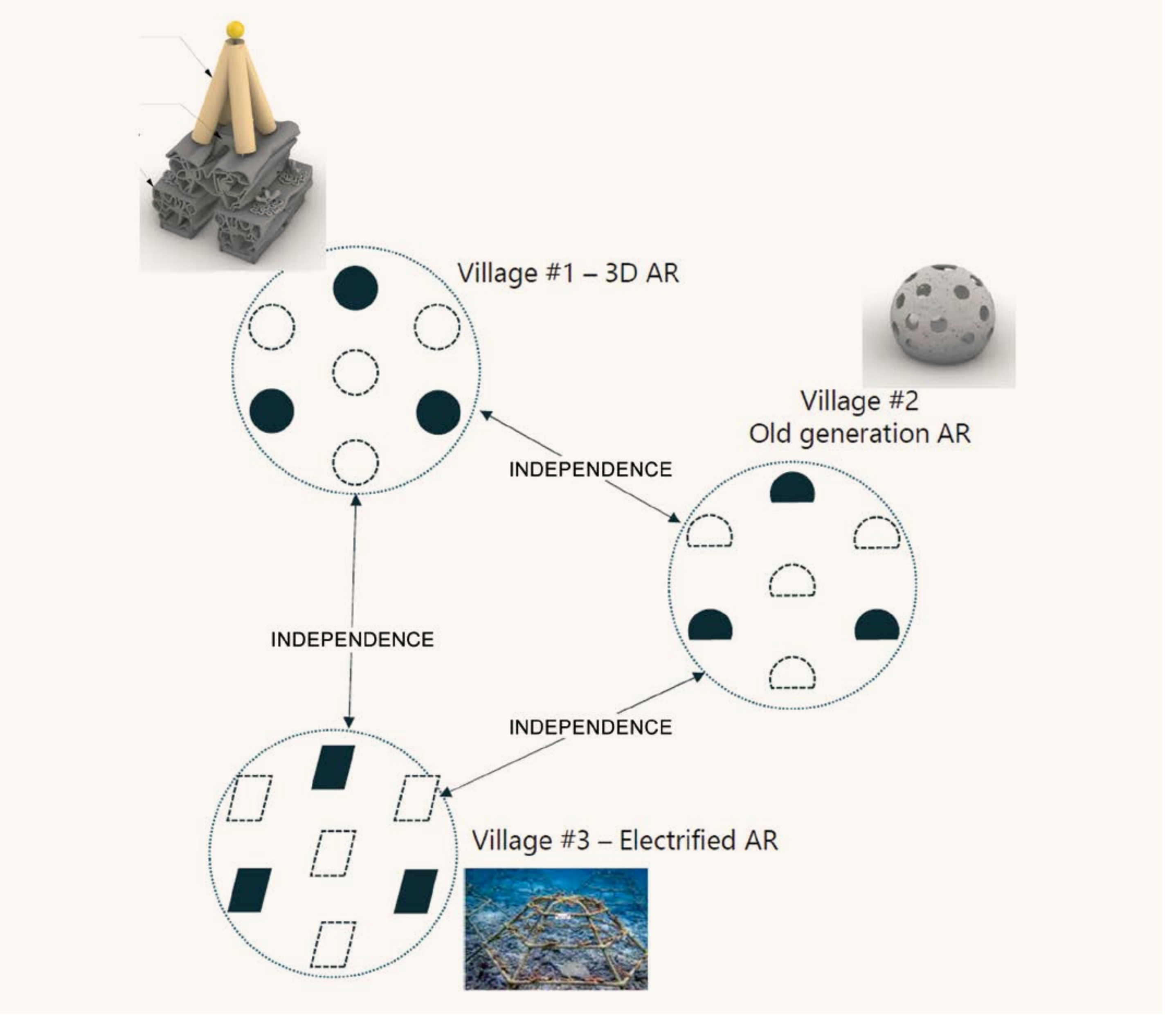


FIGURE 9

Arrangement of artificial reef villages.

more effective habitats, you need fewer of them compared to traditional artificial reefs for the same impact. In this way, the environmental cost of each 3D-printed unit is lower and at the same time the environmental benefits are far superior compared to the tradition design.

Pilot project on 3D-printed artificial reef

As part of one of its island reclamation projects, NMDC is undertaking a pilot to study the environmental benefits of 3D-printed reef compared to the more traditional dome shaped fish habitat. Electrified spider frame reefs are also being included in the pilot. The aim of the project is to demonstrate that the 3D-printed units provide significantly more effective habitat enhancement compared to either the traditional design or an electrified spider frame.

Figure 8 shows the 3D printing machine laying down the first few layers as well as the assembled unit ready for delivery. Figure 9 shows how villages of three units of each reef type are to be arranged with separation between to ensure independence.

The reefs will be deployed in sheltered waters approximately seven metres deep. Periodic marine ecology surveys will be undertaken to monitor growth in populations of marine fauna and coral in and around the reef villages. The results for each village will be compared both to each other and to two reference sites: one consisting of a natural coral reef in the area, and another similar to the deployment site but without reefs. The methodology will include diver-based surveys for fish counting and reef colonisation, as well as the use of marine camera traps.

Future opportunities

A favourable outcome from the pilot

project is anticipated that will demonstrate the advantages of the 3D-printed reef. Developers are increasingly concerned about the impact of their projects on the marine environment and we expect there to be increasing demand for artificial reefs units in the future. Having already demonstrated the benefits of the 3D-printed reefs in the pilot project we hope to be better positioned to pursue these opportunities in future.

Conclusion

By conducting projects as fish domes and 3D-printed artificial reefs, NMDC is committed to advancing initiatives that align with the United Nations' Sustainable Development Goals (SDGs), as shown in Figure 10. The efforts of restoration significantly contribute to the following Sustainable Development Goals (SDGs):

- **SDG 9 Industry, innovation and infrastructure:** The creation and implementation of these structures require innovation, the use of sustainable materials and a focus on long-term ecological health. Additionally, the practice can stimulate local economies through sustainable tourism, as artificial reefs often attract divers and snorkelers interested in exploring these man-made marine ecosystems.

- **SDG 14 Life below water:** Artificial reefs, which are man-made structures placed in the ocean to mimic the functions of natural reefs, help to restore and enhance marine biodiversity, providing habitats for fish, invertebrates and other marine species. The goal seeks to prevent further degradation of marine ecosystems and artificial reefs play a key role in rebuilding coral habitats.

- **SDG 12 Responsible consumption and production:** By utilising recycled materials such as concrete and minimising environmental impacts during the deployment process. As part of corporate social responsibility (CSR) initiatives, the company makes tangible contributions to the global effort to protect and restore marine environments.

- **SDG 17 Partnerships for the goals:** The marine environment restoration work is a joint effort by several companies, organisations, and research institutes from various countries. Together we innovate and design specific, sustainable artificial reef structures. NMDC takes an active

The cost and environmental benefits of 3D-printed units are far superior to traditional design.

FIGURE 10

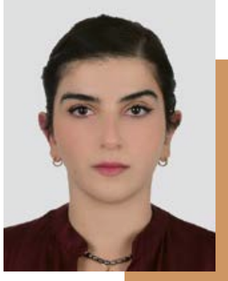
The United Nations Sustainable Development Goals.

role in fostering global partnership aimed at achieving sustainable development goals. This goal emphasises the importance of partnerships to drive progress across all goals, and the shared expertise and resources brought together through these collaborations help all the partners to advance innovative solutions for marine restoration.

In conclusion, the UAE's rapid transformation from a subsistence economy to a global powerhouse is deeply intertwined with its strategic use of dredging and reclamation projects. These efforts have been pivotal in expanding land for infrastructure and urban growth, particularly in a country with limited natural land availability. It is also recognised that, as the country continues to grow, the importance of environmental stewardship has never been more evident.

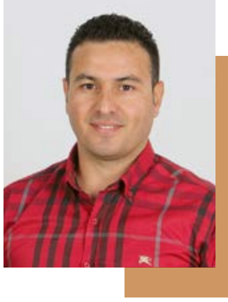
The commitment of the dredging community to sustainable practices, especially in marine habitat restoration, demonstrates how the dredging community can align with the UN Sustainable Development Goals. Through initiatives like the deployment of artificial reefs and the innovative use of 3D printing technology, we are not only addressing the environmental impacts of dredging but also actively contributing to the restoration of marine ecosystems.

By focusing on long-term ecological health and biodiversity, these projects ensure that the UAE's ambitious development plans are balanced with a responsibility to preserve the natural environment. This integrated approach highlights the potential for the dredging community to play a key role in advancing both economic growth and environmental sustainability, paving the way for a more resilient and sustainable future for the UAE.



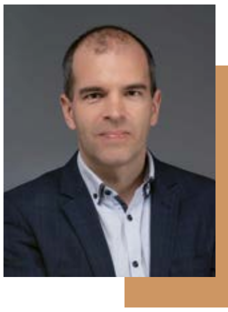
Maryam Alyahyaei

Maryam is a Senior Dredging Production Engineer with over five years' experience in NMDC. With a master's degree in water and environmental engineering, she specialises in managing dredging projects, optimising production processes and ensuring operational efficiency. In addition to this, Maryam works in Research and Development, where she focuses on driving innovation and developing cutting-edge solutions to enhance operational efficiency.



Volkan Ersozlu

With a degree in civil engineering, Volkan specialises in marine dredging, as well as onshore and offshore construction for international projects. He is currently serving as the Project Engineering Manager at NMDC in Abu Dhabi, UAE, where he leads a wide range of key projects.



Jonathan Keith

As Engineering Manager within NMDC Dredging & Marine business unit, Jonathan is responsible for managing engineering and design activities. Leveraging NMDC's own expertise as well specialists from our engineering partners, he delivers innovative solutions for tenders and awarded projects. Jonathan is actively involved in a number of initiatives to enhance the marine environments where we work.

Xiuhan Chen

Xiuhan works for NMDC as Dredging Development Manager, focusing on research and development tasks for dredging process and equipment. He is also actively involved in the World Organization of Dredging Associations (WODA), where he is general sectary to the WODA Technical Orientation Committee (TOC).

Mathilde Michaud

With a background in environmental engineering, Mathilde is a project manager at Seaboost, developing and managing nature inclusive maritime infrastructure projects. She is also a professional diver and follows projects from design to construction including underwater monitoring. Mathilde has been involved in several projects and development actions of Seaboost to implement habitat modules for marine infrastructures to boost their capacity to support marine life, innovative artificial reefs and coral transplantations.

Summary

With this article we examine the implementation of artificial reefs along the UAE coastline as a sustainable approach for marine biodiversity restoration. Together with the strategic dredging and reclamation projects reshaping the coastline, artificial reef structures, including fish domes and advanced 3D-printed reefs, have been deployed to mitigate ecological and environmental impacts.

These engineered habitats enhance marine biodiversity by providing shelter, promoting coral growth, and restoring fish populations. The study details the design, construction, and environmental benefits of these efforts, emphasising their role in ecosystem rehabilitation. By integrating innovative marine restoration techniques, the UAE aligns its coastal development with United Nations Sustainable Development Goals, ensuring long-term ecological resilience.

References

Delgado P.A. (2016)
The United Arab Emirates case of economic success: The federal government economic policies. (Doctoral dissertation).

Folpp H.R., Schilling H.T., Clark G.F., Lowry M.B., Maslen B., Gregson M. and Suthers I.M. (2020)
Artificial reefs increase fish abundance in habitatlimited estuaries. *Journal of Applied Ecology, 57*(9), 1752-1761.

Komyakova V., Chamberlain D. and Swearer S.E. (2021)
A multi-species assessment of artificial reefs as ecological traps. *Ecological Engineering, 171*, 106394.

MIT News (26 March 2024)
Retrieved from Artificial reef designed by MIT engineers could protect marine life, reduce storm damage. https://news.mit.edu/2024/artificial-reef-designed-mit-engineers-protect-marine-life-reduce-storm-damage-0326

The National (1 January 2024)
Retrieved from What is the UAE Centennial 2071 plan and why is it important? https://www.thenationalnews.com/uae/2024/01/01/what-is-the-uae-centennial-2071-plan-and-why-is-it-important/

UPCOMING COURSES AND CONFERENCES

Dredging and Reclamation Seminar
17-21 November 2025
Holiday Inn Atrium
Singapore

About the seminar

Since 1993, the IADC has regularly held a week-long seminar developed especially for professionals in dredging-related industries. These intensive courses have been successfully presented in the Netherlands, Singapore, Dubai, Argentina, Abu Dhabi, Bahrain and Brazil. With these seminars, IADC reflects its commitment to education, encouraging young people to enter the field of dredging and improving knowledge about dredging throughout the world.

For whom

The seminar has been developed for both technical and non-technical professionals in dredging-related industries. From students and newcomers in the field of dredging to higher-lever consultants, advisors at port and harbour authorities, offshore companies and other organisations that carry out dredging projects. Attendees will gain a wealth of knowledge and a better understanding of the fascinating and vital dredging industry.

In the classroom

There is no other dredging seminar that includes a workshop covering a complete tendering process from start to finish. The in-depth lectures are presented by experienced dredging professionals from IADC member companies. Their practical knowledge and professional

expertise are invaluable for in the classroom-based lessons. Among the subjects covered are:

- the development of new ports and maintenance of existing ports;
- project development: from preparation to realisation;
- descriptions of types of dredging equipment;
- costing of projects;
- types of dredging projects; and
- environmental aspects of dredging.

Site visit: seeing is believing

Practical experience is priceless and it sets aside this seminar from all others. There will be a site visit to a dredging project or yard of an IADC member to allow participants to view and experience dredging equipment first-hand to gain better insights into the multi-faceted field of dredging operations.

Networking

Networking is invaluable. A mid-week dinner where participants, lecturers and other dredging employees can interact, network, and discuss the real, handson world of dredging provides another dimension to this stimulating week.

Certificate of achievement

Each participant will receive a set of comprehensive proceedings and at the end of the week, a certificate of achievement in recognition of the completion of the coursework. Full attendance is required to attain the certificate.

Costs

The fee for the week-long seminar is EUR 3,100 (out of scope EU VAT). The fee includes all tuition, proceedings, workshops and a special participants' dinner, but excludes travel costs and accommodations. We can assist you in finding a hotel or accommodation.

For more information and how to register visit https://bit.ly/Seminar-SGP25

Dredging for Sustainable Infrastructure Course

18-20 November 2025
Holiday Inn Atrium
Singapore

How to achieve dredging projects that fulfil primary functional requirements, while adding value to the natural and socio-economic systems. This is just one of the questions addressed during the 3-day course that is based on the philosophy of the book, *Dredging for Sustainable Infrastructure*.

Experienced lecturers will describe the latest thinking and approaches, explain methodologies and techniques, and demonstrate through engaging workshops and case studies, how to implement the information in practice.

During the course, participants will learn how to implement the sustainability principles into dredging project practice, through answers to the following questions:

- What is the role of dredging in the global drive towards more sustainable development?
- How can water infrastructure be designed and implemented in a more sustainable and resilient way?
- How can the potential positive effects of infrastructure development be assessed and stimulated as well as compared with potential negative effects?
- What equipment and which sediment management options are available today?
- A brief introduction to the question, "What knowledge and tools are available to make sound choices and control a project?"

Register for the course at https://bit.ly/DfSI-SGP25

Enhance your skills and contribute to sustainable development!

IADC SAFETY AWARDS 2025
CALL FOR SUBMISSIONS

Affirming the importance of safety
Dredging activities can be risky operations with hidden dangers among heavy machinery. In response, the dredging industry pro-actively maintains a high level of safety standards. A representative of contractors in the dredging industry, IADC encourages its own members, as well as non-members participating in the global dredging industry, to establish common standards and a high level of conduct in their worldwide operations.

IADC's members are committed to safeguarding their employees, continuously improving to guarantee a safe and healthy work environment and reducing the number of industry accidents and incidents to zero.

Recognising advancers of safety
IADC conceived its Safety Award to encourage the development of safety skills on the job and reward individuals and companies demonstrating diligence in safety awareness in the performance of their profession. The award is a recognition of the exceptional safety performance demonstrated by a particular project, product, ship, team or employee(s).

Two safety awards will be presented in 2025: one to a dredging contractor (also non-IADC members) and a second to a supply chain organisation active in the dredging or offshore industry. This concerns subcontractors and suppliers of goods and services.

Each submission is assessed on five different categories: sustainability; level of impact on the industry; simplicity in use; effectiveness; and level of innovation. There is no limit to the number of submissions that can be entered and the awards are open to both IADC members and all other dredging contractors.

Send in your submissions before 31 May by visiting https://bit.ly/SafetyAward2025.

The winners will be announced during IADC's Annual General Meeting in September.

2024 winner, Jan De Nul's cutter head staircase.

Winner in the supply chain category (2024), CSPECT's ALTUM telescopic pole system.

Main members

DEME Group
Head office Belgium
+32 3 250 5211
info@deme-group.com
www.deme-group.com

Dutch Dredging
Head office The Netherlands
+31 184 411 999
info@dutchdredging.nl
www.dutchdredging.nl/en

Group De Cloedt – DC Industrial N.V.
Head office Belgium
+32 2 647 12 34
office@groupdecloedt.be
www.groupdecloedt.be

Gulf Cobla (L.L.C.)
Head office United Arab Emirates
+971 4 803 7777
gc-info@gulfcobla.com
www.gulfcobla.com

Hyundai Engineering & Construction Co., Ltd.
Head office South Korea
+82 2 746 1114
webmaster@hdec.co.kr
www.hdec.co.kr

Jan De Nul Group
Head office Luxembourg
+352 39 89 11
info@jandenulgroup.com
www.jandenul.com

National Marine Dredging Company
Head office United Arab Emirates
+971 2 5130000
nmdc@nmdc.ae
www.nmdc.com

Penta-Ocean
Head office Japan
+81 3 3817 7181
poc_international_web@mail.penta-ocean.co.jp
www.penta-ocean.co.jp

Rohde Nielsen A/S
Head office Denmark
+45 33 91 25 07
mail@rohde-nielsen.dk
www.rohde-nielsen.dk

Royal Boskalis
Head office The Netherlands
+31 78 6969 000
royal@boskalis.com
www.boskalis.com

TOA Corporation
Head office Japan
+81 3 6757 3800
webmaster@toa-const.co.jp
www.toa-const.co.jp

Van Oord
Head office The Netherlands
+31 88 8260 000
info@vanoord.com
www.vanoord.com

Colophon

Editorial
For editorial enquiries, please email editor@iadc-dredging.com or call +31 (0)70 352 3334. Articles featured in *Terra et Aqua* do not necessarily reflect the opinion of the IADC Board of Directors or of individual members.

Editor
Ms Sarah Nunn

Front cover
Photo © Seaboost

Back cover
Photo © Jan De Nul

Design
Smidswater, The Hague, The Netherlands

Layout
Robert Dumay Graphic Design, Zierikee, The Netherlands

Printing
Damen Drukkers
Werkendam, The Netherlands

ISSN 0376-6411

How to subscribe?
To receive a free print or digital subscription, register at www.iadc-dredging.com/terra-et-aqua/subscribe.

Call for submissions
Published quarterly, *Terra et Aqua* is an educational and professional resource that features cutting-edge innovations to disseminate knowledge throughout the dredging industry. Are you an author, researcher or expert in dredging or a related field? Do you want to share your innovative research, papers or publications with the dredging industry? Then submit your proposals to the editor at editor@iadc-dredging.com for consideration.

Terra et Aqua is published four times a year by
International Association of Dredging Companies
Stationsplein 4
2275 AZ Voorburg
The Netherlands
www.iadc-dredging.com

MIX Paper from responsible sources FSC® C114590

carbon neutral natureOffice.com | NL-077-843295 print production


ALWAYS READY TO MEET NEW CHALLENGES
IADC stands for "International Association of Dredging Companies" and is the global umbrella organisation for contractors in the private dredging industry. IADC is dedicated to promoting the skills, integrity and reliability of its members as well as the dredging industry in general. IADC has over one hundred main and associated members. Together they represent the forefront of the dredging industry.
www.iadc-dredging.com
IADC