CAN A LAKE'S ECOLOGY BE RESTORED WITH UNWANTED SEDIMENT?

By constructing the Marker Wadden, a nature reservation is created allowing for natural processes as much as possible.

In April 2016, Boskalis started constructing one of the largest nature restoration projects in Western Europe. First and foremost a bird paradise, the Marker Wadden consists of a 1,000-hectare landscape above and below the waterline, multiple rows of dunes, and a 1500-metre trench to collect fine silt from Lake Markermeer.

The Marker Wadden project has been a long-cherished dream of the project's client, Natuurmonumenten, or the Dutch Society for the Preservation of Nature. By constructing the Marker Wadden, a nature reservation is created allowing for natural processes as much as possible. The contractor and the client were both well aware that control of nature and natural processes is often limited. The challenges that this limited control posed were not only solved technically but were also solved due to the good collaboration between both parties. This article describes some of these unique challenges – both technically as well as in terms of collaboration – and how they were solved.

FIGURE 1

The Marker Wadden is situated in Lake Markermeer.

The ecological context and purpose of Marker Wadden

Lake Markermeer is a 680 km^2 artificial lake in the centre of the Netherlands which was formerly part of the larger Zuiderzee. After the area was closed off with two dams, Lake Markermeer became a fresh water lake with unique ecological values (Natura2000 area). Over the past decades, several ecological problems have arisen related to, amongst others, highly turbid water leading to a decrease in light penetration, a decrease in biodiversity and a change in nutrients' volume and constitution (Vijverberg 2011 and De Lucas Pardo (2014)). These circumstances caused the fish population to be decimated leading in turn to a further decline in the population and variety of birds in the area. What remained was an enormous lake of untamed turbid water in the centre of the 'blue heart' of the Netherlands.

Several solutions for these problems were investigated in the research project 'Natuurlijker Markermeer IJmeer' which was initiated by Rijkswaterstaat in 2010 and finished in 2015. One of the recommendations to improve the ecological quality of Lake Markermeer was to increase the habitat diversity. Given the large size of the lake, the diversity was rather limited due to the depth of the lake. Besides, the lake has steep and hard shores, reducing the habitat diversity from water to land. Rijkswaterstaat – the Dutch Directorate General for Public Works and Water Management – together with other governmental agencies developed a vision which gives Lake Markermeer a sustainable future by proposing the development of a wetlands area in the lake. Natuurmonumenten

Not only sand, but also fine sediment and soft mud are used as a core building material.

then took the initiative for the construction of the Marker Wadden and thanks to financial contributions from the Dutch National Postcode Lottery, the Dutch Ministries of Economic Affairs and Infrastructure and the Environment, the provincial authorities of Flevoland and North Holland, several companies and Natuurmonumenten itself, the plan was turned into reality. With the Marker Wadden, an archipelago of islands and sand banks has been created that will ultimately improve the quality of Lake Markermeer by making it healthy and productive again so it will become a paradise for birds and fish as well as a place where people can enjoy nature.

The technical context of Marker

Globally, sand as a resource for land reclamations is increasingly hard or costly to come by. Alternative land fill materials and methods are being explored worldwide. The Marker Wadden is constructed using all locally available material (see Figure 2). Not only sand, but also fine sediment and soft mud are used as a core building material. The fine sediment is a thin layer (locally less than one metre) of silty sand resting on the bottom of the lake. This fine sediment layer comes into suspension during storms and presently causes the ecologically detrimental turbidity. Underneath the fine sediment lies the soft mud which is a thicker layer (locally approximately eight metres thick) of Holocene (inorganic) clay and peat. The use of these materials for large-scale land reclamations is innovative and not yet common practice, and predicting the behaviour of such reclamations is challenging. Under this thick layer of fine sediment and soft mud lies the Pleistocene sand. In traditional marine contracting, only this sand layer would be of interest. The layer on top would traditionally be considered 'unsuitable' and therefore has to be disposed of in the most cost-effective way. For the Marker Wadden, this 'unsuitable material' is a key building material. Because of

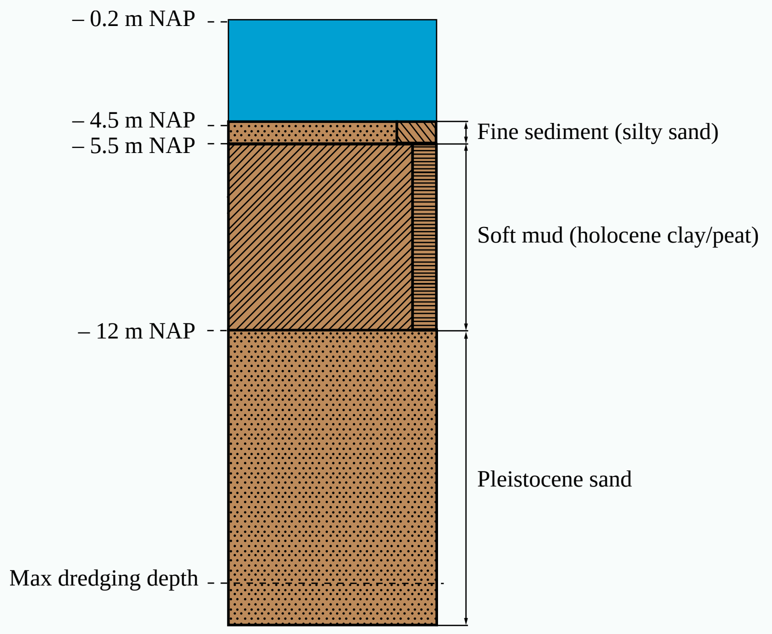

FIGURE 2

Schematic original bottom profile.

this, the Marker Wadden is a perfect example of beneficial use of sediment (CEDA 2018).

Design and construction

The design was approached from an ecological and landscape architectural perspective. The guiding principle was to create a healthy habitat for flora and fauna that maximises the ecological value of the Lake Markermeer region.

It was only later that the Boskalis team put on its more traditional engineering hat to put the plans into practice. The interaction between the various parties with the aim of orchestrating the different wishes and practicalities resulted in an exceptional design. The landscape design of the Marker Wadden was made by Vista Landscape Architects, as part of the Boskalis consortium during the tender. All discipline

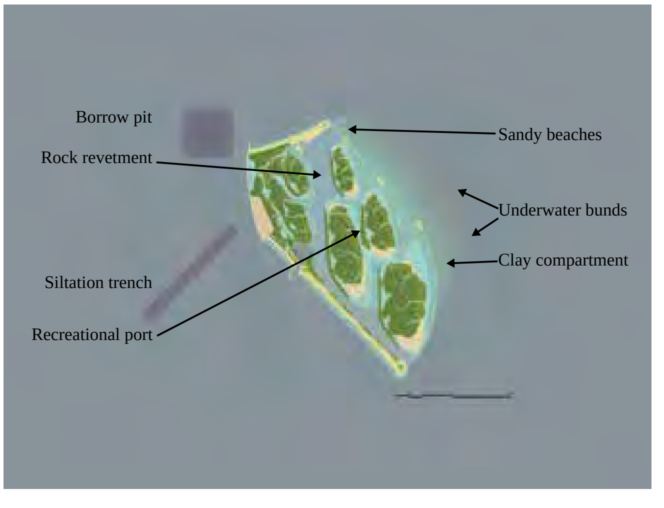

FIGURE 3

Design of the Marker Wadden project.

FIGURE 4

Construction of sandy beach and dunes (A) as well as the rock revetment at the west side of the island (B).

inputs were integrated into this design during an iterative design process allowing for a high-quality, economical design and operational work method. Figure 3 shows a top view of the design with its characteristic features.

Almost all material used for constructing the Marker Wadden – sand, soft mud and fine sediment – was collected in the borrowing pits and the siltation trench. The reclamation area is divided in several compartments divided by bunds. Sand was used to create the sandy beaches along the north and southwest shores (see Figure 4A), the underwater bunds at the east side, and the compartment bunds inside the area. Beaches, bunds and a rock revetment (see Figure 4B) were needed to protect the area from wave attack. At the edges of the beaches, a buffer volume was placed to compensate for sand transport and erosion. The main compartments, such as the swamp area indicated in green in Figure 3, were filled with soft mud and fine sediment.

The area is constructed in several steps and layers, as indicated in Figure 5. First, small sandy bunds of 1 to 1.5 metres high were constructed

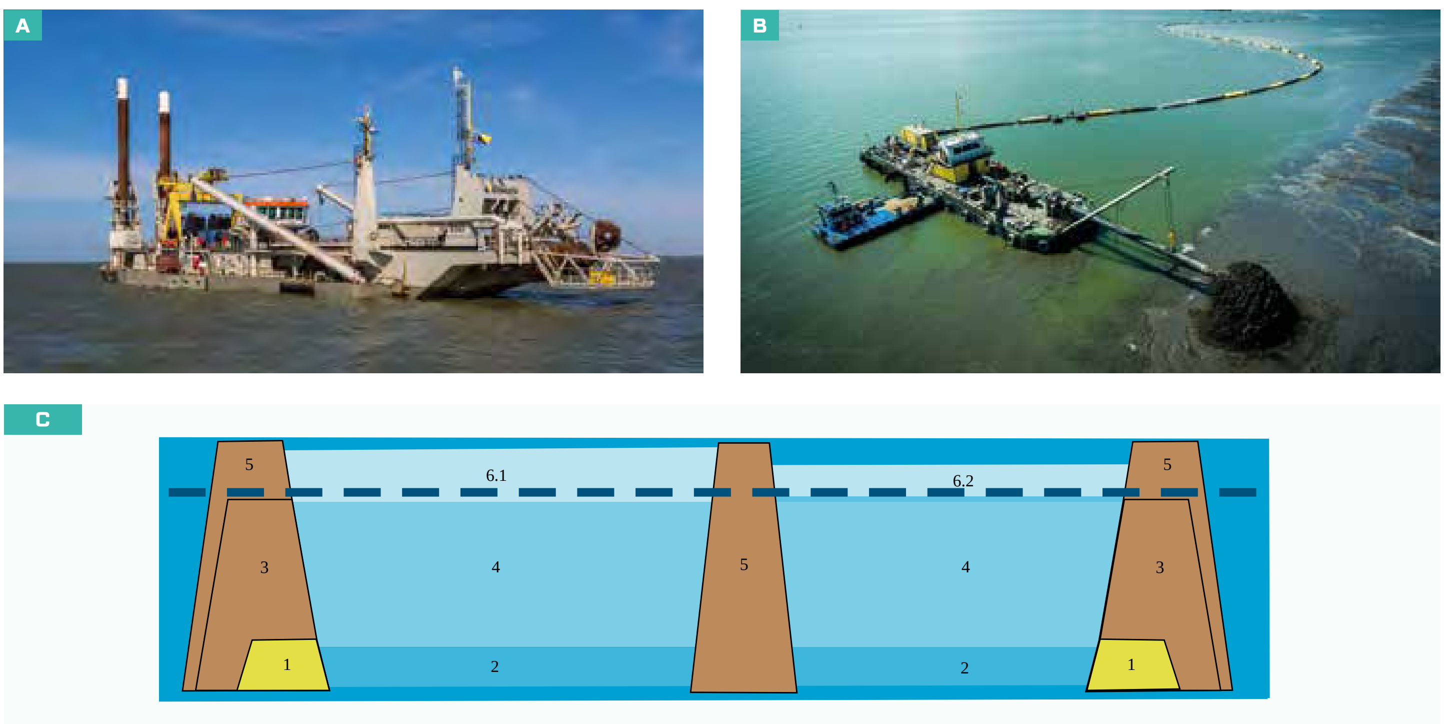

FIGURE 5

Cutter Suction Dredger Edax (A), spreader pontoon Steenbok (B), and indicative construction steps (C).

FIGURE 6

Areal overview of the Marker Wadden (situation summer 2018).

(1). The area in between was filled with a mud-water mixture (2). Next, the sandy bunds were raised up to the water level, around 0 metres (3), and in succession, the area in between was filled again with a mud-water mixture (4). The sandy bunds were then raised above the water level and sub-compartments were created by intermediate bunds (5). The sub-compartments enabled different water levels and filling rates in the different compartments. Finally, the mud mixture was pumped into the area above the lake level (6). After that, the consolidation process continued. A spreader pontoon was used to fill the compartments, allowing for the controlled installation of thin layers of soft mud. Figure 5 shows the pontoon in operation during the construction of one of the sandy bunds of Marker Wadden.

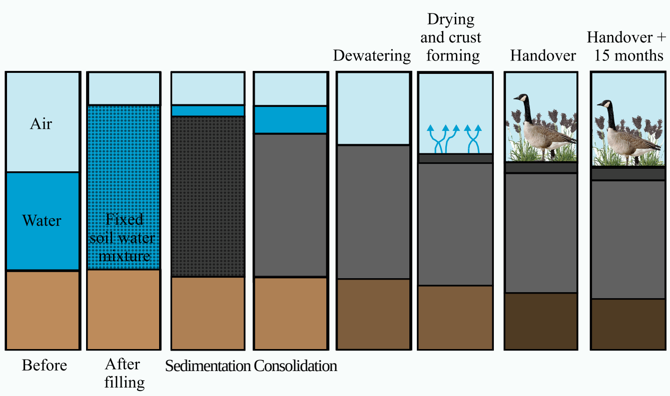

FIGURE 7

Process from reclamation to final handover condition.

Processes from reclamation to handover

Because the islands are made with hydraulically dredged material, the soft mud and fine sediment from the borrow pit is mixed with water and bulks (expands). After the bulked material is placed in the compartments, the material undergoes a de-bulking process called consolidation. This process from filling of the compartments to final strength development is indicated schematically in Figure 7. First, the compartments were filled with the dredged mixture. After reclamation, the mud and sediment starts to settle and consolidate, forming a 'clear' water layer on top. After some time, when consolidation of the bed has progressed, the water layer on top was removed and drying of the bed started, forming a dry crust on top of the soft bed. The weight of the crust on top of the soft material increased the rate of consolidation. During the design phase, the consolidation process was modelled and estimations were made for the moment in time the final bed elevations will be achieved, and if strength requirements will be met. The elevation requirements are rather strict in order to achieve an optimal ecological value for the area.

The process can only be numerically modelled to a certain extent. As we are building with nature and allowing for natural processes to assist in the construction as much as possible, extra aspects play a role in the development of elevation and strength. One aspect is vegetation (see Figure 8A). Roots of the reed plants – which are sowed after lowering of the water in the compartment – can extract water from the fill, resulting in increased consolidation rates. Vegetation also has a sediment-retaining capacity, keeping loose sediment in place. Another aspect is the morphology that is caused by water-level differences over space and time. This causes flows to occur from one compartment to another and between the compartments and Lake Markermeer. These flows can have a scouring effect (see Figure 8B) but can also result in creek formation towards outflow locations.

Real time research and adaptive management during construction

The project has a stringent set of elevation requirements. Having to meet these requirements in the face of consolidation, crust formation of the soft clay material and

FIGURE 8

The project saw the development of sown reed through natural processes.

FIGURE 9

Natural processes led to creek development caused by bund excavation. A hover craft was used to sow the reed.

all other naturally occurring effects, is rather unique and experimental. For this reason, real time research was performed and adaptive management was applied during execution of the project.

During the design phase and also execution of the project, testing on various scales was performed: column testing in a laboratory, container scale testing and testing in the actual reclamation. Many of these tests were executed by Boskalis together with universities to verify consolidation parameters, crust formation and monitoring techniques. The effect of vegetation is also part of research projects at universities (Smart Ecosystem project).

Adaptive management was applied during the construction phase. Before construction, the margin of error in modelling the behavior of the compartment fills was significantly larger than the margin in contractual elevation requirements. The understanding of the behaviour of the fill material was constantly updated based on monitoring and analysis. This way, the reclamation process was controlled. The monitoring data was used to validate or correct our predictions and to support project execution. There was anticipation on operational or requirement-related problems if the soil material behaved differently than expected. When necessary, the work method was adjusted.

To support the adaptive management, different types of measurements were carried out:

- When the compartments were still underwater, bed levels of the fill material were measured with both a single beam echo sounder and a multi beam. The survey was carried out on a fixed grid system to guarantee coverage of the area and to compare different surveys in time.
- Vertical density profiles from the fresh bed to the original bed were taken at various locations inside the compartments, using a Hydramotion MudBug (Hydramotion company). Before the Marker Wadden's construction started, different systems to measure the density were tested. The MudBug performed best for the Marker Wadden fill material (Kleine Schaars, 2016). Density profiles were measured directly following completion of a fill layer and then at regular time intervals (see Figure 10). These measurements gave an idea about the evolution of the density profiles and the settlement/consolidation over time
- Aerial topography measurements of the bed levels inside the compartments were carried out after the compartments were filled and the water levels were lowered. Quarterly measurements were carried out using a Topcon Sirius Pro drone, an unmanned aerial vehicle (UAV) installed with a high-resolution camera,

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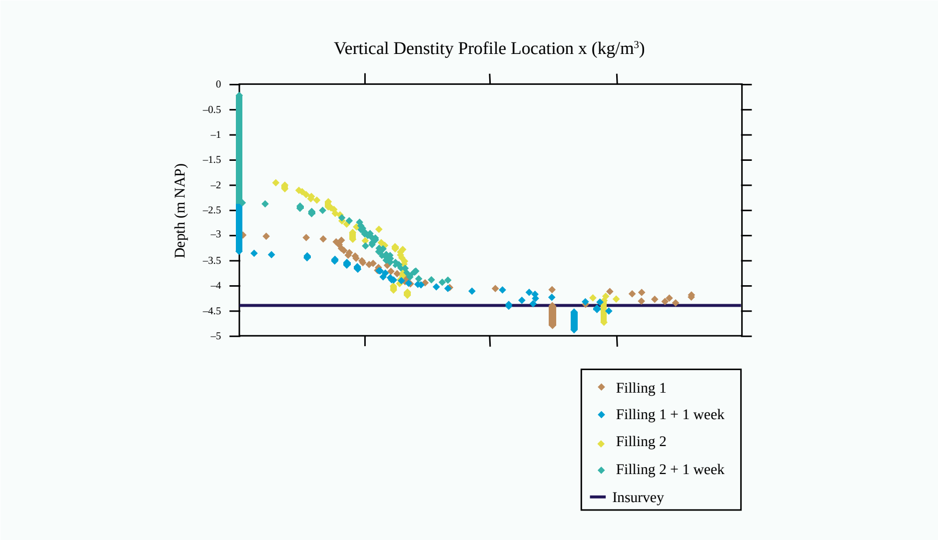

FIGURE 10

Density profile evolution over time after two consecutive fillings.

used for stereo photogrammetry. By comparing the topography data from every quarter, the contractor was able to evaluate the behaviour of the soil in the compartments. Together with the density information from the MudBug, additional filling layers were designed to finally end at the correct bed level. Figure 11 shows a typical result of the 2D drone survey.

FIGURE 11

Example of 2D topography data, measured with a drone.

- The behaviour of the sandy shores was monitored frequently just after initial construction. Bathymetry measurements underwater were carried out with a survey boat equipped with a multibeam echosounder (SeaBat 7101). Topographic profile measurements of the beach and the shallow beachfront were carried out with handheld GPS equipment (Trimble R10 – GNSS System). Beach profiles were analysed on cross-shore as well as longshore sediment transport processes. These analyses provided the contractor information about the initial behaviour which was useful to determine the final profiling of the beaches and dunes. More information to be found in Steetzel (2017).

- Settlements of the sandy bunds, beaches and hard revetments just after construction were measured with 'classical' settling plates. Observations were compared with the original settling calculations during the design phase. Where needed, final construction heights were adapted based on the monitoring of the behaviour. This enabled the contractor to finalise the bunds and revetment at a proper level such that future settlement is covered by the surplus height of the structures.

- In August 2017, a first part of the Marker Wadden – the part which was above water at that moment – was sowed with reed seeds to start vegetation development. Sowing was carried out in a specially designed way, with a hoover craft. (see Figure 9) In a smaller part of the area, vegetation development was started with reed rhizomes, for example along the shores of the port. After sowing, the reed started to germ and grow. During this period, frequent monitoring was carried out to follow the development process. Parameters like plant density (plants/m^{2}), height and stem thickness were systematically determined to determine success rates of vegetation development.

The contractor's understanding of the various objects was greatly increased based on the real-time analysis of field measurements, observations, numerical design modelling and the operational lessons learned. Because of the integrated adaptive management process, we were able to continuously optimise the work method to reduce the risk of not fulfilling the project requirements. The following construction method components could be adjusted with respect to the compartment filling: management of the compartments (size, number of filling layers and water levels), mixture density and production rates of the dredger, time interval between the filling layers, and filling volume distribution over individual compartments.

Collaboration and contract

Contractor Boskalis and client Natuurmonumenten/Rijkswaterstaat have a strong mutual drive towards meeting the project's ecological goals. Apart from the apparent intrinsic motivation, this drive is strengthened by the way the contract and collaboration were set up. The client is not intrinsically interested in technical specifications such as elevation, bearing capacity, density and so forth. The explicit interest is in ecological value. This is strongly reflected by the project requirements. One good example is the formulation of the 'goose

FIGURE 12

Goose footprints can be seen on top of the compartment fill.

accessibility' requirement: the client formulated this as a functional requirement in the tender specification. The contractor translated this requirement to a set of technical values – in terms of undrained shear strength – to check feasibility of this requirement. However. if during project execution it is clear that geese can walk on the compartments, this undrained shear strength does not have to be established.

This requirement is a testament to the client's attitude, which was to ensure that there was room for a skilled contractor to operate in a way that best serves the client's intrinsic goals.

Although the tender was set up towards designing and pricing of 300 hectares of wetland area, initially only the western-most island was be constructed (180 hectares). In case extra funding would become available and the execution of the first island was successful, the second island could be contracted as well. This is a strong example of setting the formal stage such that contractor would be as motivated towards meeting the project goals as the client. The additional islands were contracted in 2016 and 2017.

One of the starting points was to allow for natural processes as much as possible. By accepting these processes, natural forces have had a big influence on what the Marker Wadden looks like (see Figure 13). When unexpected results were witnessed during construction of the island, the client was not focused on jumping to corrections. On the contrary, a local pocket of shells or an occasional high-spot which was not intended beforehand or explicitly in line with the design became welcome as they diversify the habitat. Being allowed to, in collaboration, optimise the final design and construction of the islands allows then for more economical construction and for more ecological value.

FIGURE 13

Supported by vegetation development, natural processes have created a diverse landscape near the hydraulic fill locations.

Lessons learned and first successes

Perhaps the most important lesson learned is the way in which client and contractor collaborated. Starting at the conception of the Marker Wadden, throughout the tender phase and execution, the client set the stage by creating the (formal) boundary conditions that ensures that successful execution is mutually beneficial. An example of this was the client requirement to ensure that the public can experience the islands from the earliest moments. This was needed for public support and finance.

In addition, client and contractor shared the same project office from the start of execution which allowed for open and transparent communication, frequent informal contact, a proactive attitude and easy adaptation towards mutually beneficial results (one final project goal). As a result, above the initial one, in total five islands were contracted and constructed by contractor, in time and within budget, resulting in an even greater ecological improvement for the Markermeer region.

The first ecological research findings are very promising. Not only is a variety of bird species visiting the islands, but also insects have settled on the islands. In the surrounding

FIGURE 14

Birds found their way to the Marker Wadden early on during construction.

waters, a dramatic increase of plankton is being observed providing an important food source for fish and birds in Lake Markermeer.

The good positioning of the Marker Wadden from an ecological point of view became apparent during early construction. Many bird species were attracted the moment land over water was created (see Figure 14). In fact, some of the areas were temporarily closed

FIGURE 15

Turning a nuisance into ecological value.

The good positioning of the Marker Wadden from an ecological point of view became apparent during early construction.

for personnel and equipment during breeding season.

The main technical breakthrough is the use of soft mud and fine sediment as a core building material. The main challenge is to place the fill material such that the height requirements are met after consolidation. Before execution started, the uncertainties of the self-weight consolidation of hydraulically placed clay was larger than the margins within the contractual requirement. By applying adaptive management, this uncertainty was dealt with. Also, allowing for natural processes resulted in a more economical construction of the Marker Wadden. In doing so, larger habitats could be constructed for the fixed budget.

Because soft mud and fine sediment are used as a core building material, a precedent is created that may change at the perception towards the world's most available resources. Soft mud and fine sediment are generally considered to be unsuitable for construction and a costly nuisance to dispose of. The Marker Wadden project proves that this material, if used correctly, may be a valuable resource (see Figure 15). In fact, it was the source of the ecologically detrimental turbidity and used to improve the ecology. Soft mud and fine sediment exhibit highly varying characteristics at each project but the same construction (floating equipment) and design principles as applied for the Marker Wadden project can be applied to other projects around the world. This makes the Marker Wadden project a valuable pioneering example for how to reclaim large volumes of soft mud and fine sediment.

Summary

In April 2016, Boskalis began construction on one of the largest nature restoration projects in Western Europe which is first and foremost a bird paradise. The Marker Wadden consists of a 1,000-hectare landscape above and below the waterline, multiple rows of dunes, and a 1500-metre trench to collect fine silt from Lake Markermeer. The project has been a long-cherished dream of the project's client, Natuurmonumenten, or the Dutch Society for the Preservation of Nature, and forms a nature reservation which allows for natural processes as much as possible. The contractor and the client were both well aware that control of nature and natural processes are often limited, and the challenges that this limited control posed were not only solved technically but were also solved due to the good collaboration between both parties. This article describes some of these unique challenges – both technically as well as in terms of collaboration – and how they were solved. The main technical breakthrough is the use of soft mud and fine sediment as a core building material.

REFERENCES

CEDA (2019)
Sustainable Management of the Beneficial Use of Sediments: A Case-studies Review. In preparation from Working Group on Beneficial Use of Sediment.

De Lucas Pardo, A. (2014).
Effect of biota in fine sediment transport processes: A study of lake Markermeer. Phd thesis, TU Delft.

Kleine Schaars, L.C. (2016).
Meetsensor selectie project Marker Wadden. Bachelor thesis, Hanzehogeschool Groningen.

Steetzel, C. (2017).
The behavior of the sandy shore of the Marker Wadden. The morphological development of sandy shores in a lake system and application of design formulae and models. MSc Thesis, University of Twente.

Vijverberg, T., Winterwerp, J.C., Aarninkhof, S.G.J., Drost, H. (2011).
Fine sediment dynamics in a shallow lake and implication for design of hydraulic works. Ocean Dynamics, 61:187–202.

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Roeland Lievens
After obtaining his Hydraulic Engineering degree from Delft University of Technology, Roeland Lievens worked at Royal Boskalis Westminster as a Marine Morphological and Environmental discipline engineer. Roeland was involved with the Marker Wadden as a Project Engineer since the start of construction. Specifically, Roeland was responsible for setting up and executing the monitoring and analysis of the hydraulic fill behaviour, increasing the understanding of building with soft mud and fine silt.

The project has been a long-cherished dream of the project's client, Natuurmonumenten, or the Dutch Society for the Preservation of Nature.

Jeroen van der Klooster
Working for 15 years at Boskalis, Jeroen van der Klooster is currently Project Manager for the Marker Wadden project. He received his BSc in Environmental Engineering in 2003 from the HTS in Utrecht, the Netherlands.

Roel Posthoorn
Roel Posthoorn is working as 'project director Marker Wadden' for Natuurmonumenten, the Dutch Society for the Preservation of Nature. Roel is the initiator of the Marker Wadden and responsible for the management of the project for the clients of Rijkswaterstaat and Natuurmonumenten. He has a degree in environmental studies as well as in forestry and nature management.

André Rijsdorp
André Rijsdorp is director of Plan&Proces, a strategic consultancy in spatial development and ecological restoration. From the first day, André was involved in the set-up of Marker Wadden and the funding and collaboration needed for the realisation of the project. He plays a key role as 'entrepreneur' in the development and lay out of the islands. André has a BSc degree in Landscape Planning.