Contact
Noordeinde 109b
3341 LW Hendrik Ido Ambacht
+31 (0)6 18 74 99 48
info@ecoshape.nl
www.ecoshape.nl

Memo

To	Luca Sittoni, Erik van Eekelen
From	Erik Hendriks
Authored by	Erik Hendriks, Ebi Meshkati Shahmirzadi, Frank Hompes, Marcel van den Heuvel, Thomas Vijverberg, Thijs van Kessel
Reviewed by	Luca Sittoni, Jan Tigchelaar, Frank Hompes
Project	Living Lab for Mud – Overarching research
Date	21 December 2021
Subject	Practical guidelines for Building with Mud projects

1 Introduction

This document provides practical guidelines for Building with Mud (BwM) projects. These are based on a combination of fundamental research and operational lessons learned from two EcoShape large-scale pilot projects: the *Marker Wadden pilot experiments*[1] (Deltares, 2021; Hanssen and Verheul, *in prep.*) and the *Clay Ripening Pilot*[2] (EcoShape, 2020).

Mud is a material rich in fine particles, smaller than 63 µm. Mud is generally (initially) soft and undergoes large settlement. It is a complex building material, as its properties can vary strongly in both time and space. Successfully applying mud as a building material relies on understanding and controlling its material properties.

To understand the lessons learned from the considered pilot projects, this report starts by discussing the BwM concept (Section 2). In this section, we discuss the underlying physical processes and possible measures to control these during design and execution of projects. These measures are mainly based on experience gained during both pilots. Afterwards, the lessons learned during the Marker Wadden pilot experiments and Clay Ripening Pilot are discussed (Section 3). Both projects are first introduced and then discussed in more detail, focusing on how the material properties were controlled and which practical issues were encountered. To conclude, the main take-aways are summarized (Section 4).

2 Building with Mud concept – physical ripening

2.1 Physics

The BwM concept mainly concerns turning soft (dredged) sediment into soil. Therefore, it focuses on understanding and controlling ripening. Though ripening of mud involves physical, chemical and

[1] https://waterinfo-extra.rws.nl/projecten/lijst-projecten/kennis-marker-wadden/kennis-innovatieprogramma-marker-wadden/

[2] https://eemsdollard2050.nl/project/pilot-kleirijperij/

biological processes, only physical ripening is considered here. Despite that these processes occur in parallel, physical ripening is dominant (Van der Meulen, 2012; after Pons and van der Molen, 1973).

Physical ripening is a process in which the mechanical behaviour of a given mud with a certain quality is improved (transformed) to a level that can be used in an application of interest. Within this process, several means and tools can be used to achieve the goal. The choice for any of these means/tools depends on initial mud quality, budget, time, climate, space, and philosophy (Figure 1). For most large-scale engineering applications, a mud deposit undergoes three main phases during the ripening process:

- (hindered) settling;
- self-weight consolidation;
- desiccation.

During all three phases, there is a water flux from within the mud deposit to outside of the deposit. Eventually, this results in a denser deposit. However, the driving force behind this water flux differs. For settling the driving force is gravity, while for self-weight consolidation it is a combination of gravity and excess pore pressure gradients. For desiccation, it is surface evaporation. The settling phase generally lasts for hours to a day, while consolidation and desiccation may take months or years, strongly dependent on layer thickness, drainage and climate conditions. For a detailed description of these phases and associated processes, the reader is referred to the literature survey by Meshkati et al. (2021). This guideline focuses on the main concepts only.

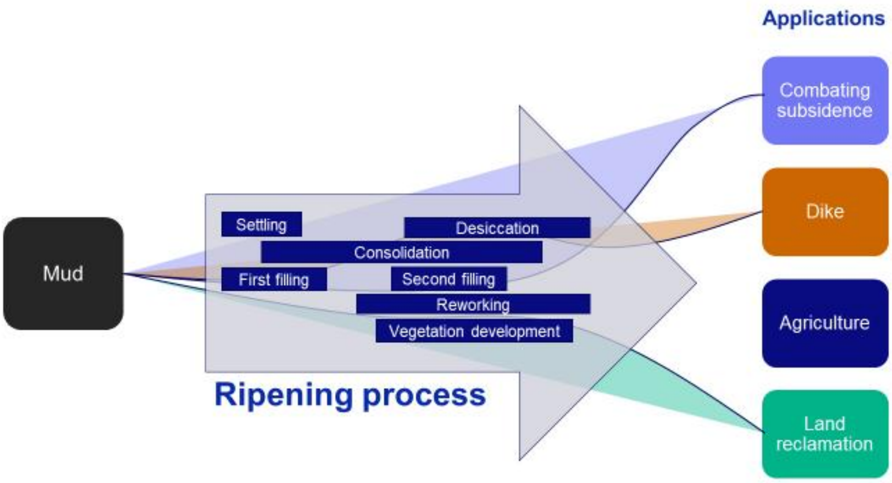

Figure 1: Physical ripening is a process in which the mechanical behaviour of a given soil (mud) with a given quality is improved (transformed) to a level that can be used in an application of interest. Within this process, several means and tools can be used to achieve the goal. The choice for any of these means/tools depends on initial mud quality, budget, time, climate, space, and philosophy.

The exact settling, consolidation and desiccation behaviour of mud depends on various (bio-) physico-chemical microscopic factors, their interaction and interdependence under the influence of ambient conditions, as shown in Figure 2. Identifying these microscopic factors often requires dedicated laboratory techniques. These techniques are well-established but are material- and labour-intensive and thus costly. To overcome this issue, scientists and engineers use the concept of lumped modelling as a global approach to link physico-chemical microscopic properties of mud to its macroscopic behaviour.

In such a lumped modelling approach, the effect, interaction and interdependence of microscopic details are summarized into one or a few overarching parameters or functions. These are called (lumped) material parameters or (lumped) material functions. For mud (and soil), well-known material functions are (Figure 2):

- void ratio-permeability relation;
- void ratio-effective stress relation;
- shrinkage and swelling curve;
- water retention curve;
- Atterberg limits.

These material function can then be incorporated in models to predict the (long term) settlement and density development of a deposit. A similar approach can be followed for desiccation studies. Lumped modelling provides a less complicated and less costly approach than identifying microscopic factors. However, it is very important to measure and critically assess these lumped parameters. They vary according to different physio-chemical states of a deposit. Thus, it is vital to understand their evolution throughout the ripening process, since a ripening deposit experiences several distinguishable physicochemical states during its lifetime.

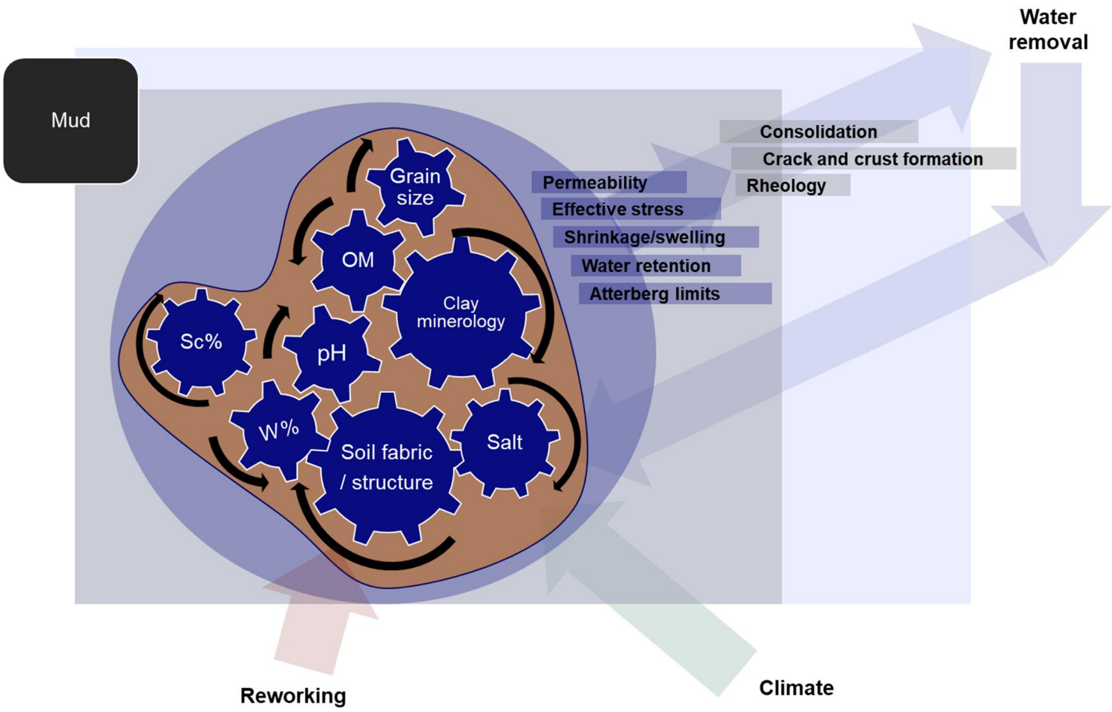

Figure 2: Microscopic physico-chemical interactions in mud (in the brown area), lumped material functions used to describe them (top right corner) and external influences on material behaviour (bottom).

2.2 Control measures

We stated before that successful application of mud as a building material depends on controlling its material properties. Possible control measures in both the design and execution phases of BwM projects are listed in Table 1. For each measure, its effect and how to monitor it are specified.

Table 1: List of control measures, their effect and how these measures can be monitored

Control measures	Effect	How to monitor?
Category 1A: fill design and project planning		
Layout of fill design (w.r.t. bathymetry)	Basin dimensions and its shape affect the flow patterns in a fill. Therefore, they also affect mud layer thickness and segregation of sediments in mixture (fine/coarse material) and the outflow of fines. Generally, the fill surface will have a downward slope from the filling point to the far end of the fill.	N/A

	When the objective is to create several layers with small thicknesses this may be a challenge.	
Filling layer thickness, frequency of filling and waiting time between layers	Filling layer thickness has a considerable effect on consolidation speed. The consolidation period is quadratically related to layer thickness. For desiccation, the following order of magnitude applies: a 0.4 m thick layer fully desiccates between 6 months (spring-summer time) to a year with minimum reworking required. A 1.5-meter-thick layer takes more than 3 years, requiring a moderate to high amount of reworking.	Deposit height, if above water table: Settlement beacons, installed prior to filling. UAV, i.e. drones. Piezometers, standpipes. If (part of) the deposit is submerged: Multibeam / singlebeam.
Drainage (bottom drainage and horizontal sand layers)	Drainage increases consolidation speed. Theoretically, drainage at the bottom maximally decreases the 1D consolidation period by a factor 4. In practice, this strongly depends on local conditions. Horizontal sand layers will only improve drainage if they are alternated with muddy layers and if they have a free outlet from the deposit. They may then shorten the drainage path of the muddy layers. Sandy lenses in the deposit will not improve the consolidation process. Moreover, they limit the depth of cracks, slowing down desiccation.	Piezometers. Water volume discharge.
Subsoil conditions underneath fill area (thickness, composition, etc)	The soil beneath a mud deposit can provide natural drainage, if it consists of very permeable material. If this is the case, it accelerates the ripening process. If the subsoil is compacted due to increased loading by the mud deposit, this may lead to overall settlement. The top of the mud deposit will then be lower.	In-situ testing prior to filling and soil sample analysis. For compaction: Settlement beacons, founded on the subsoil.
Planning of ripening with respect to climate conditions	Very important factor. Ripening should be an activity where the speed of the whole process is tuned with climatic conditions. Dry periods (spring, summer) have a positive impact on the ripening process. A tropical climate also has a positive impact on the ripening process. (avoid rainy seasons)	Measure: - Rainfall; - Temperature; - Humidity; - Evaporation.
Category 1B: filling process		
Filling material density	Density of filling material influences (hindered) settling, consolidation speed and the desiccation process.	Measurement aboard the vessel. In-situ testing (if site is accessible): Density probes penetrating the soil. Collect soil samples from deposit and analyse in lab.
Filling speed / discharge / production rates	Discharge rates and filling speed affect the initial filling density and segregation process. This influences the settling and initial consolidation process. Filling duration should also be considered. Within weeks, a thin layer may settle considerably.	Measurement aboard the vessel.
Composition of filling material (%sand, %clay, %organic matter)	If the filling material is heterogeneous, segregation occurs during filling of the basins. Coarser sand particles settle close to the inflow point, leading to differences in height, composition and density in a fill. Desiccation occurs in the crust under the influence of the atmosphere (oxygen). A crust forms, which will develop cracks due to shrinkage. Crust formation in low density muddy deposits is accelerated by wide and deep cracks. Crack depth determines the thickness of the crust. When the sediment is sandier or when the initial density is higher, the cracks will become less wide and less deep, resulting in a thinner crust which	Collect sediment samples prior to construction and during all ripening phases. Ideally at different locations and depths in the deposit. Determine grain size distribution, including percentage of clay particles and organic matter content.

	desiccates slower. When the material contains more than 30% sand, cracks will be filled up with sand after rain, and the thickness of the crust will decrease further. Underneath the crust, only consolidation of the mud occurs.	
Desalination of sediment mixture by adding fresh water	Desalination is very difficult after the mud has been brought into the basins. Adding fresh water when pumping mud into the basins works better. The downside is that dilution leads to a lower initial density. When the mud is pumped below the gelling concentration (i.e., the structural density) this does not matter anymore.	Measure chloride content. Crucial factor: check which protocol to be followed in a certain country / jurisdiction / project.
Category 2: deposit control		
Water level control	Water level and deposit height determine when the material will be above or below water table. This determines the start of the desiccation phase, which happens when the deposit interfaces with the atmosphere. If the mud deposit is placed on land: possible outflow of water (weir boxes) influences the start of ripening.	Installation of standpipes, tide gauges.
Vegetation development	Desiccation initially goes as deep as the roots of vegetation go. Eventually desiccation will go deeper, depending on which part of the deposit is in contact with the atmosphere.	Regularly measure root depth vs desiccation depth.
Reworking of material	Mixing the dried top layer with underconsolidated layers underneath should be prevented as much as possible. Harvesting the dried top layer works best. By removing the top layer, a new part of the deposit will be exposed to the atmosphere. If no drainage is present, unripened mud should be reworked on ridges to increase exposure to climate. When drainage is present, clay fields (ripening within compartments without reworking) can be used.	Measurement of: - Density; - Water content; - Crust thickness after reworking. Check water content when ridges can be formed (usually the Liquid Limit). When the first dried crust is available, check the max Proctor density of the end result. This gives an indication on densities during the process. Water content is key in this process, relative to the Atterberg limits.
Use of artificial additives to improve soil conditions	Use of flocculants to increase settling or binders (e.g. cement, etc) to increase strength of the material.	N/A
Use of intermediate production steps to improve soil conditions	All of the above steps can be combined, e.g. with intermediate steps to come to a final best solution	N/A

3 Project experiences

Project experiences from the two large-scale pilot projects are shared here. This section is divided into three main subparts, outlined below:

1. Brief introduction of pilots:
    a. Marker Wadden pilot experiments
    b. Clay ripening pilot
2. Factsheet outlining main characteristics of both pilots (Table 2)
3. Lessons learned during pilots
    a. Final requirements
    b. Material properties of interest
    c. Control measures

3.1 Introduction of Marker Wadden and Clay Ripening pilot projects

Marker Wadden pilot experiments

The Marker Wadden pilot experiments form part of the overall Knowledge and Innovation program Marker Wadden (KIMA). This pilot is carried out in 3 dedicated compartments (in Dutch referred to as '*Dun Slib'* compartments), specially created within the larger Marker Wadden project. In these compartments consolidation and crust formation are studied in detail.

The Marker Wadden project aims to create a large-scale wetland in the Markermeer, the Netherlands. The main building material consists of soft mud, resulting from remoulding and diluting Holocene marine clay deposits dredged from the bed of the Markermeer. The soft mud is contained within large compartments made of sand bunds to provide the necessary shelter against waves and currents. The soft mud gradually consolidates and if the top layer is above the water table a crust develops. To provide a proper wetland habitat and proper conditions for ecological development, the final surface elevation of the mud layer should neither be too high nor too low with respect to the water table. The question is how the desired end state can be reached as efficiently as possible, within reasonable time and with limited risk and uncertainty.

Clay Ripening pilot

The Ems-Dollard is characterized by high turbidity and, therefore, reduced ecological value. To enhance the water quality and mitigate nautical constraints due to siltation of mud in harbours, several pilots have been carried out to extract excess mud from the Ems-Dollard system. One of these pilots is the Clay Ripening Pilot project, which investigates the transformation of mud into suitable clay (soil) for dike revetment or construction. Various natural and mechanical ripening scenarios are applied in twenty-five separate basins to identify the most effective method for transforming fluid mud into soil. No additives (e.g. flocculants) were added to the dredged mud.

Apart from producing dike clay, the Clay Ripening Pilot aims to develop knowledge, tools and a business case about the ripening of clay and the possibilities for scaling up.

3.2 Pilot projects factsheet

Table 2: Pilot project factsheet

	Marker Wadden pilot experiments	**Clay Ripening pilot**
Goals	• Understand the consolidation and ripening processes in a real field situation; • Quantify effect of following steering/environmental parameters on consolidation and ripening processes: - filling layer thickness; - mud composition; - water level control; - vegetation development.	• Generate knowledge, methods and tools for transforming fresh marine mud into clay (soil) suitable for dike construction; • Deliver 70.000 m^3 of clay as suitable construction material for the Demonstration Project i.e. "Brede Groene Dijk" (BGD); • Present a business case on the complete chain from the dredging of mud to delivery of clay for dike construction.
Total volume	Total volume: initial volume 440.000 m^3	Initial volume: 270.000 m^3
Deposit layout	3 compartments, area 100.000 m^2 (Figure 4, Appendix A.1)	25 ripening basins, spread over two locations: - *Delfzijl*: 200.000 m^2. 15 basins on the landward side of the dike along the Delfzijl port entrance channel; - the *"Kwelder"*: 70.000 m^2. 10 basins adjacent to the BGD location. Each basin is approximately 100 x 100 m^2
Minimum/ maximum deposit depth	Min / Max deposit depth: 4 m water layer. One filling layer in the 2 Southern compartments, and 2 filling layers in the Northernmost. Estimated initial filling density in TDS (Tons Dry Solids): approx. 1.2 TDS/m^3 (average)	Initial filling height of 50 to 200 cm. In some basins, multiple fillings took place.
Project duration	2019-2021	2018-2022
Require-ments (type)	Deposit height related to water table, density and surficial strength.	Material properties for dike clay (a.o. density, salt and organic content)

3.3 Lessons learned Marker Wadden pilot experiments

3.3.1 Final requirements

For the regular Marker Wadden compartments, requirements were imposed on deposit height and surface strength. Successful execution of the project depended on predicting and controlling deposit height, strength and density, given the applied mass of solids per unit area, sediment properties, subsoil properties, water level control and vegetation development.

No strict requirements on final height, strength or density were imposed for the pilot compartments. Here, the main requirement was to accurately monitor the settling, consolidation and crust formation, to learn about building with mud and wetland creation.

3.3.2 Material properties of interest

For the ripening process during this pilot, key parameters proved to be: sediment layer thickness (dependant on TDS), thickness of dry layer (crust) and water level fluctuations. Because of the fill size and sediment density & composition, sediment spread heterogeneously through the compartments.

Within the physical processes of settling, consolidation and desiccation, complex interactions occur between different parameters. Specific mud characteristics (percentages sand/clay/silt, organic content, pH) at a location in the compartments finally determine deposit behaviour. Changes in environmental conditions possibly affect different parameters, which can result in a change or restart of the processes. Continuous changes in forcing can result in an increase or decrease in deposit settlement and thus total height.

Apart from settling, consolidation and desiccation, subsoil settlement also proved to be a significant process.

For a more detailed description of monitoring carried out in the Marker Wadden pilot experiments, see Appendix A.1.

3.3.3 Controls in project design and execution

Table 3: Lessons learned about control measures during Marker Wadden pilot experiments

Control measure	Lessons from *Marker Wadden pilot experiments*
Design of fill layout (w.r.t. bathymetry)	Coupling of multiple fill basins is an efficient way to keep all fine sediment (building material) in the project. Filling of basins requires process water which needs to flow out. If one basin only is used, fine sediment will flow out and will not be used efficient for building reclamations. Even with relatively small compartments (when compared to large 'regular' Marker Wadden basins), substantial heterogeneity in density and sediment composition across one compartment develops. If this is undesired, then very small basins are needed, which can result in inefficient use of bund material. Big compartments result in more difficult water level control, more wave generation on the water level and thus erosion of bunds. If dynamics are important (topography, waves, currents) then big compartments are better.
Subsoil conditions underneath fill area (thickness, composition, etc)	Subsoil settlement under placed load is primary concern, depending on local drainage conditions of the subsoil. In some locations, subsoil settlement has the same order of magnitude as the mud deposit settlement.
Planning of ripening with respect to climate conditions	Ripening goes fast in spring and summer period. The maximum observed crust thickness over longer period is few dm's. Best optimal solution for ripening cannot be seen separate to other requirements, such as vegetation development and strength requirements.

	The final project aim determines the best strategy when and how to start the ripening process with respect to meteorological conditions.
Filling material density	Density decreases with distance from the filling point in a fill. Initially this creates level differences over a fill, however due to different natural process (e.g. wave action when water layer is on top) this can also be levelled out, reaching a flat bed. For nature projects, differences in levels are required to get diversity in habitats. For other types of projects (e.g. land reclamations for port construction or housing) this might be unwanted. To reach a flat bed, this requires more homogeneous high-density profiles over the whole fill.
Filling layer thickness, frequency of filling and waiting time between filling layers	One larger filling layer has some serious drawbacks: - Requires large volumes at one time → requires high ring dikes and large supporting volumes of e.g. sand; - Difficult to steer to the final best solution. Too much → too high, too little → too low; - When filling a basin, process water needs to flow out. When one filling layer is applied this leads to more losses of the fine fraction out of the basin. Using multiple filling layers gives more flexibility to come of the final best solutions → is a better steering parameter. Using only one layer provides less options to steer the process.
Composition of filling material (% sand, %clay, %organic matter)	Fines percentages increase with distance from the filling points. This has also a relation with density profiles. For nature projects: important to limited sand fraction, mud and organic material is necessary to create ecological habitats.
Water level control	Water level control is one of the most powerful steering parameters to come to a best final solution and control the processes (consolidation, ripening and vegetation development). However, controlling water level proved difficult, for a variety of reasons, such as: costs, sand availability, pump capacity, meteorological conditions. .
Vegetation development	Importance of water level control and protection against feeding birds. Water level in the basins determine the conditions for vegetation development.

3.4 Lessons learned Clay Ripening Pilot

3.4.1 Final requirements

At the start of the project, the following requirements for clay delivery to the BGD had been defined. These are the base requirements suggested by the *Technische Adviescommissie voor de Waterkeringen* (TAW) for dikes:

- Erosion class: 1 or 2
- Liquid limit > 40
- Plasticity Index (*PI*): > 18
- Sand percentage < 40%
- Clay percentage 20 – 40% (guideline, not a requirement)
- Consistency index (I_c) > 0.6
- Organic content < 5%
- Salt content of porewater < 4 g/l

To meet these requirements, salt, organic material and water needed to be removed from the dredged mud during the ripening process. In the first 2 years of the pilot, salt and organic content levels did not drop. The very dry summers during these years possibly caused the salt content to go up, due to evaporation in the crust and no rain to wash the salt away. In the last 2 years of the pilot, a decrease of salt and organic content was observed. However, in the meantime the requirements had already been adapted. Only the consistency index-requirement still had to be met, but additional conditions applied:

in a parallel pilot project, it should be proven that the final product is suitable to construct a dike, regardless of the salt and organic content.

3.4.2 Material properties of interest

The following parameters are of interest:

- Water content;
- Atterberg Limits;
- Consistency index (i.e. comes from Atterberg limits and water content);
- Organic content;
- Salt content;
- Percentages of clay, silt, and sand (grain size distribution);
- Crust and crack development as an indication of dewatering and oxidation;
- Groundwater table since it influences the performance of bottom drainage.

All these parameters changed during the ripening process, except for the grain size distribution. The following processes are of interest:

- The effect of organic and salt content on Atterberg Limits;
- Crust and crack forming and development (thickness of crust and pattern of cracks);
- The effects of the percentage of sand on the ripening process (Kwelder location);
- The effects of bottom drainage through the bottom sand layer and drainage pipes underneath the mud on the ripening process (Delfzijl location);
- The effect of surface water regulation, aiming to steer the start of ripening;
- The effect of reworking;
- The effect of seeding pattern and vegetation type.

For a more detailed description of monitoring carried out in the Clay Ripening pilot, see Appendix A.2.

3.4.3 Controls in project design and execution

Table 4: Lessons learned about control measures during Clay Ripening pilot

Control measure	Lessons from *Clay Ripening* pilot
Design of fill layout (w.r.t. bathymetry)	The mud deposits all had a horizontal surface after filling. Hence, layer thickness depended on the bed level within the basins.
Filling layer thickness, frequency of filling and waiting time between layers	*Delfzijl:* Most basins were filled in 2 phases (2x +/-1m) with 3 months waiting time in between. The crust that was formed on the surface of the first layer during these 3 months was never found back after the second filling. This implies that the dried-out layer of the first round of filling became wet again after the second-round layer placement filling. The first conclusion is that filling in 2 layers did not give the result that was hoped for. Furthermore, additional costs of keeping the equipment (e.g. pipelines, valves, etc.) on the terrain were relatively high. *Kwelder:* Filling took 3 months with various layers (25 cm thickness) for each basin. Waiting times in between to let the suspension settle resulted in higher densities at the end of the filling time. During filling, the layers were submerged and thus not exposed to the atmosphere.
Drainage (bottom drainage and horizontal sand layers)	*Delfzijl:* In twelve basins, a 20 cm sand layer was brought in with drainage pipes to provide bottom drainage. Drainage layer of sand (20 cm) and drainage pipes started to work immediately; during the first months a continuous flow of water exited through the drainage pipes. This stopped gradually after 9 to 12 months' time, which was much longer than expected. In three basins, the mud was brought in directly on top of the clayey subsoil. The clay-ripening process in these three basins was much slower than in the other twelve basins. *Kwelder:*

	Dewatering through the weir boxes was difficult because of the depth of the main dewatering pipeline and variations in water levels. No bottom drainage was present.
Subsoil conditions underneath fill area (thickness, composition, etc.)	*Delfzijl:* Clayey subsoil. As there were no demands regarding total deposit height, subsoil settlement was not a primary concern for this pilot. *Kwelder:* A clayey subsoil was present in all basins, which lies slightly lower than the surrounding terrain.
Planning of ripening with respect to climate conditions	Climate and seasonal variations are crucial in planning a clay ripening site. If only density is of interest, the ripening process will be on hold during a wet or cold winter season. The muddy deposit should be closed and sealed off from incoming rain by placing the ripened mud in thick layers, densified by mechanical means (bulldozer/crane). Also, it is essential that the mud is maximally exposed to the atmosphere during the summer or hot/dry months. When salt removal is also of interest, exposing the deposit to precipitation may accelerate the salt removal process. However, this slows down the desiccation process.
Filling material density	*Delfzijl:* Mud that was pumped into the basins had a density of 1.20 TDS/m^3, which lies above the gelling concentration of 1.16 TDS/m^3. This means that no settling of the particles took place, and thus right from the beginning after deposition, consolidation started. The density increased slowly, due to desiccation at the atmosphere and consolidation in the layer below. *Kwelder:* The pumping distance to the basins was about 8 km. The initial pumping density of the mud was much smaller than at the Delfzijl location (<1.10 TDS/m^3) and below the gelling concentration.
Composition of filling material (% sand, %clay, %organic matter)	*Delfzijl:* Mud dredged from the Delfzijl approach channel was homogeneous. The deposited mud in the basins was also homogeneous both along the depth of deposit as well as across the basins (inlet towards weir box). Due to the absence of sand in the mud, no segregation took place during the filling process. Generally, there was less than 1% sand, and more than 50% clay. Occasionally, some higher sand percentages were measured, caused by mixing of the drainage layer with the ripened clay (mainly clay from basin D7). *Kwelder:* The filling material was more heterogeneous than at the Delfzijl location. This resulted in segregation of sand near the pipe outflow during filling of the basins. This resulted in different grain size distributions, both horizontally and vertically within basins, and between the various basins. The sediment in the basins had a sand content of above 50% (by weight) close to the inlet, gradually reducing to less than 5% (by weight) near the weir boxes. Segregation of the filling material led to interesting observations. The sediment which deposited close to the inlet was much sandier than the rest of the basin. The result was that cracks did not form or were much smaller and less deep and the crust was relatively thin. Therefore, air did not enter the sediment layer very deeply and thus, desiccation hardly took place. Also, because of the staged filling, a sandwich layering formed with sandier and more clayey layers intersecting in the vertical. The sandy layers were locked up and became over-pressured with water from the more clayey layers. The evidence of this process was clearly visible during the excavation of these layers after one year. The layer thickness decreased much more near the weir boxes. Here, the initial water content was higher, which led to a thicker crust with deeper cracks. This caused more consolidation and desiccation. After reworking the layers, the sandier layers dewatered quicker. Underneath the crust of the more clayey layers, not much had happened after one year.
Desalination of sediment mixture by adding fresh water	Desalination can be achieved by adding fresh water and mixing this with the sediment. Adding fresh water during pumping process worked better than adding fresh water after the mud had deposited in a basin.
Water level control	*Delfzijl:* There is no settling, so there is no need to drain surface water through the weir boxes during filling. *Kwelder:*

	Weir boxes were very important during the filling process. Settlement of the sediment and draining surface water was crucial in the process.
Vegetation development	Five so-called biological basins (3x Delfzijl, 2x Kwelder) contained crops to study the effects of vegetation on the ripening process. The roots entered the clay 40 to 50 cm. They enhanced the dewatering process of the deposit by evapotranspiration. The root development also brought oxygen into the deposit. The ripening process went as deep as the roots, vegetation only developed in non-cracked areas of the deposit.
Reworking of material	When the dried out top layer was mixed with the unripened layer underneath, the dried-out material rewetted and the desiccation process had to start over again. Hence, mixing the dried top layer with the rest of the deposit should be prevented. Harvesting the ripened top layer is preferred. Hereby, the layer underneath is exposed to the atmosphere. If no drainage is present, unripened mud should be reworked on ridges to increase exposure to climate. This can be done when the mud has a water content of approximately the Liquid Limit. In general: minimize reworking as much as possible. Let the atmosphere do the work.

4 Main take-aways: control measures, practical aspects and monitoring

Many control measures exist when it comes to the ripening process. These both exist in project design and execution. Essential control measures are discussed here, including a summary in bullets of relevant practical aspects.

- Most importantly, the best strategy for a fill depends on the final requirements:
  - Requirements and climate conditions determine the ripening strategy. This includes when and how to start the ripening process.
  - For wetland creation, the required strength of the surface layer is relatively small. In this case, the main challenge is to efficiently use the building material. The best strategy would then be to construct the fill using multiple low-density layers, letting thin crusts form on each layer. In this case, most of the vertical profile is not dry, so not overconsolidated. This results in efficient material use, i.e., a large volume while using only a limited amount of TDS. If most of the profile is overconsolidated, too much sediment is used for this specific purpose.
  - If the fill is used for construction purposes, this requires stricter strength and settlement conditions. Hence, overconsolidation is necessary. Intermediate steps of drying the material are possibly required before transporting material to the final fill (e.g. first ripening the material first, then rehandling it as a reclamation fill). To make this cost efficient, ripening and reclamation sites should be nearby or even at the same location.

- General recommendations:
  - Minimize reworking as much as possible. Let the atmosphere do the work.
  - Desiccation starts when sun, wind, oxygen, rain can reach the soil.
  - Horizontal transport is expensive and troublesome, especially by road. Ripening and application sites should be nearby, preferably at the same location.

- Design of fill layout:
  - Location of inflow and outflow point as well as dimension and shape of a basin determine the discharge patterns in the fill and segregation of sediments in mixture as well as the percentage of fines leaving the fill.
  - Using one fill basin may lead to a large outflow of fine sediment, which is subsequently lost for building purpose.
  - Coupling multiple fill basins keeps fine sediments within the project and results in efficient material use.
  - Even in smaller basins, substantial heterogeneity in density and sediment composition across the basin can occur (in case of non-homogeneous filling material).
  - Bigger basins/compartments can be subjected to wave generation which causes erosion of bunds.

- Fill layer thickness, frequency of filling and waiting time between fill layers:
  - Layer thickness is critical, choice depends on mud properties, climate, available time, and space.
  - Consolidation time increases quadratically with layer thickness.
  - Multiple fill layers provide more flexibility and are a better steering parameter to come to the desired final situation. With one fill layer there are less options to steer the process. However, filling a basin using multiple layers is more time consuming and more expensive compared to filling once.
  - A crust which is formed after certain waiting time on the surface of an intermediate layer will not be found back after installation of a subsequent layer since the dried-out layer will become wet again. (Kleirijperij: 3 months waiting time).
  - Staged filling can lead to sandwich layering where clay and sandy materials are segregated in separate layers.

- Drainage:
  - Drainage layer of sand (20 cm) in combination with drainage pipes has a positive effect on the drainage process. This is especially the case when the subsoil itself is clayey.

- Sand trapped in a muddy deposit has an adverse effect on the ripening process, as it limits the depth of cracks in the deposit, thereby slowing down desiccation.

- Subsoil conditions underneath fill area:
  - When deposit height is compared to a fixed reference level, subsoil settlement due to increased loading by the mud deposit is an important factor. Subsoil settlement may be of the same order of magnitude as settlement of the mud deposit itself.
  - An in-situ clay layer directly underneath a basin filled with dredged mud causes a slow ripening process. Ripening proceeds faster when more permeable material (i.e., sand) is present underneath a basin.

- Planning of ripening with respect to climate conditions:
  - Climate and seasonal variations are crucial in planning a clay ripening project.
  - Think in seasons. Bring in the material at the beginning of the warm/dry season (NL – March). Ensure the deposit is ready for use at the end of the season (NL – October). Finetune layer thickness on what can be achieved in a single season.
  - If density and water content are the only parameters of interest, the deposit should be closed and sealed off from incoming rain during cold and wet periods (autumn/winter). For instance, by means of placing the ripened clay in thick layers, densified by mechanical means. During warm and dry periods (spring/summer) the deposit needs to be exposed maximally to the atmosphere.

- Filling material density:
  - Lower pumping densities increases segregation during the filling process.
  - Because of segregation, density in a basin decreases with increasing distance from the filling point, which may create level differences over a fill.
  - Reaching a flat surface requires more homogeneous high-density profiles over the fill.
  - A higher water content leads to a thicker crust with deeper cracks. This causes more consolidation and desiccation. Underneath a crust not much happens.

- Filling speed / discharge / production rates:
  - Quality over quantity; in general: lower speeds and rates are more favourable with respect to consolidation and stability.

- Composition of filling material
  - The particle size distribution of the fill material impacts the sedimentation process in a basin. If present, coarser particles (sand) will deposit close to the inlet and hamper the formation of crust and cracks.
  - Fines percentage increases with distance from the inlet.
  - Assess Atterberg limits and relation to the mud/clay water content in all stages. Calculate, predict, monitor volumes always precisely in relation to water content and density (saturated and unsaturated).
  - Sand generally increases drainage capacity and causes less cracks in dried top layer

- Desalination of sediment
  - Desalination can be achieved by adding fresh water and mixing this with the sediment.
  - Adding fresh water during pumping process works better than adding fresh water after the mud has deposited in a basin.

- Water level control
  - Water level control is complex, but one of the most effective control measures to come to a best final solution. Through water level control, consolidation, ripening and vegetation development can be regulated.
  - Water level control is more suitable/practical in smaller basins/compartments.
  - If the mud deposit is placed on land, possible water outflow through weir boxes.

- Vegetation development
  - The roots of crops enhance the dewatering process of the deposit by evapotranspiration.
  - The root development brings oxygen into the deposit.
  - Initially, the ripening process goes as deep as the roots. Eventually, desiccation may progress deeper into the deposit, depending on water table level.

- The water level in a basin determines the conditions for development of vegetation.

- Reworking of material
  - Mixing of top layer of dried clay with unripened soft clay layer underneath should be prevented. Harvesting the ripened top layer is preferred.
  - In case no drainage: unripened soil to be set up on ridges.
  - In case of drainage: remove the ripened top layer, expose layer underneath to the atmosphere.

Monitoring

Monitoring is an important aspect during a BwM project, as monitoring data can be used to introduce modifications in the ripening process via the control measures. An essential aspect of monitoring is resolution in both time and space. The largest changes in material properties occur in the first months after filling the deposit. Hence, temporal resolution during the initial months should be sufficient to capture these changes. If segregation is likely, the spatial resolution needs to be high. This results in a significant number of samples which must be collected over the fill area. Obtaining sufficient temporal and spatial resolution is not easy, as access to the deposit is hampered by its low bearing capacity. Furthermore, monitoring expenses should be justified compared to project budget.

In both pilot projects, data was mainly used to monitor what happened on site. Based on project experiences, the minimum of required monitoring for BwM projects is listed in Table 3. Ideally, tests on fill material should be carried out not only when filling the deposit but also as the deposit develops with time.

Table 5 Minimum of required monitoring for BwM projects

Tests on fill material (soil testing)	Monitoring
Bulk density	Subsoil settlement: settlement beacons (above water) and Single-beam / multibeam survey (below water)
Grain size distribution, including hydrometer test	Thickness and volume of mud layer: Settlement beacons (above water) and Single-beam / multibeam survey (below water)
Water content	In-situ strength and density over depth: Density probes / CPTu's
Atterberg Limits	Water level in fill: Standpipes and tide gauge
Organic content	Groundwater table: Standpipes
Salt content	Pore water pressures in mud layer: Piezometers
Sulphate and Chloride content	Crack and crust development
Proctor test (on dried crust)	EC and pH of drained water (in case of bottom drainage present)
Permeability of soil	Weather data (rainfall, temperature, humidity, evaporation)
Pore water composition - nutrients	Water quality of groundwater and ditches
Shrinkage and swelling behaviour	GHG emission
Water retention behaviour	
Permeability of soil	

From monitoring to adaptive management

To go from monitoring to adaptive management of deposits, it is crucial to increase monitoring resolution. As this is not trivial, several suggestions are provided based on project experiences:

- Facilitate easy on-site testing;
- Include monitoring demands as early as possible in the design phase of projects;
- Be flexible in monitoring (monitor when major events take place instead of at fixed intervals);
- Apply simple and automated measuring techniques at the deposit site;
- When appropriate, use remote sensing techniques (satellite, UAV's).

5 References

Deltares. (2021). Synthese rapport KIMA CONCEPT 1.0 (15 december 2021) Rapportage over de eerste vijf jaar onderzoek op Marker Wadden

Ecoshape. (2020). Monitoringsrapportage Klerijperij. Rapportage 2018, 2019 en 2020 Kleirijperij Delfzijl.

Hanssen, J., Verheul, M. (2022). Resultaten monitoring dunslibcompartimenten, Deltares report (*in prep.*)

Meshkati Shahmirzadi, E., Hendriks, E., van Kessel, T., Kox, M., van der Star, W. (2021). Literature review and conceptual model for the ripening of mud. Memo, Deltares project 11206339-001. TKI Living Lab for Mud overarching research, Phase A.

Pons, L.J., van der Molen, W.H. (1973). Soil genesis under dewatering regimes during 1000 years of polder development. Soil Science 116, 228-235.

van der Meulen, J.P. (2012). Modelling of Ripening Behaviour of Albian Oil Sand Tailings in Canada, Master thesis, TU Delft.

A Pilot project experiences

A.1 Marker Wadden pilot experiments

Visual impressions from the Marker Wadden pilot compartments are shown in Figure 3. Figure 4 shows their location on the Marker Wadden.

Figure 3: Images taken at Marker Wadden pilot experiment compartments

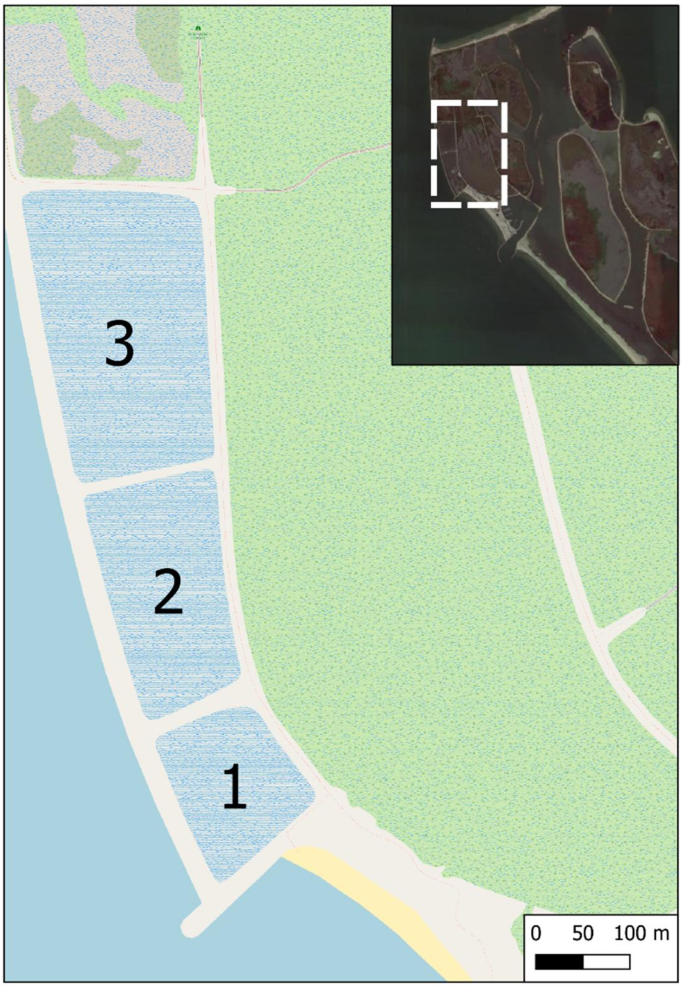

Figure 4: Location of pilot experiment compartments on Marker Wadden

Monitoring

Figure 5 gives an overview of measurement locations for the pilot experiments. The following data were measured:

- Subsoil settlement;
- Thickness of mud layer;
- Water level;
- Pore water pressure in mud layer;
- In-situ strength and density profiles;
- Sampling in 10 vertical profiles (4×, i.e. in 2019, 2×2020 and 2021) with subsampling and tests in geotechnical lab on:
    - water-, solids and organic content
    - bulk density
    - Atterberg limits
    - Grain size distribution or %<63 μm
    - Pore water composition w.r.t. nutrients.

Practical lessons learned from the monitoring are:

- Filling is a challenge

- strong gradients in height and composition, relocation of nozzle and second filling layer necessary;
- Water level control is a challenge
  - available pumping capacity, permeability of dams, depth of drainage channels, height of surrounding compartments, landscaping works, etc.;
- Vegetation growth is a challenge
  - linked to water level management, elevation, filling layers;
- Access is a challenge
  - trip to Marker Wadden
  - access to sampling locations in thin sludge
  - breeding season
- Limited ability to control conditions, i.e. emphasis on monitoring what is happening.

(Very concise) scientific lessons learned from the monitoring are:

- Importance of subsurface settlement;
- Importance of water level control;
- Limited influence of vegetation on consolidation, physics dominates in the early years;
- Evaporation is your friend (to gain strength quickly) and enemy (as it increases total settlement);
- (dPw/dz)_consolidation = $\Delta\rho g \approx 5$ kPa/m (max); (dPw/dz)_suction pressure ≈ 100 kPa/m;
- Converting soft mud into a wetland is faster and easier than expected;
- The challenge is to keep it stable.

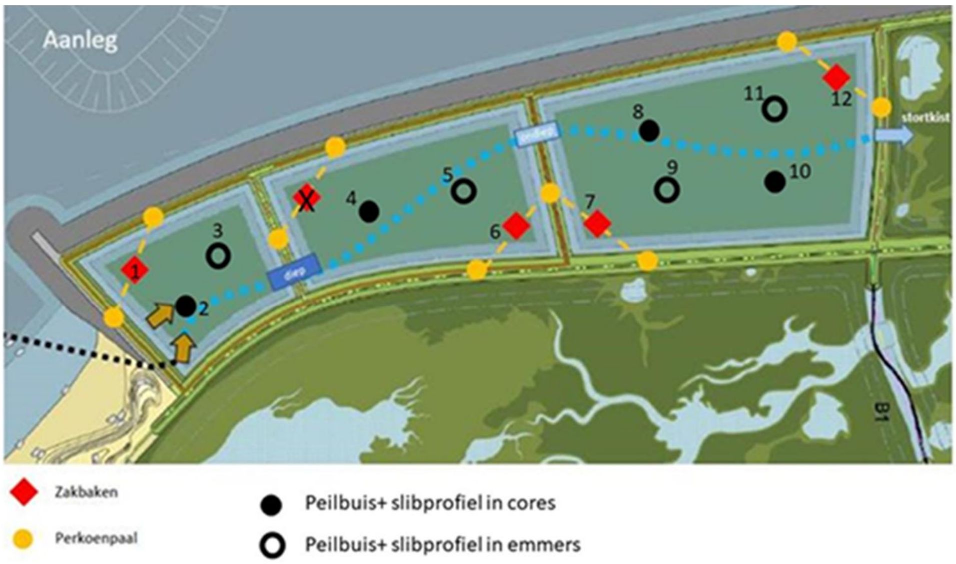

Figure 5: Overview of measurement locations in Marker Wadden pilot experiment compartments

A.2 Clay Ripening pilot

Monitoring

In this pilot project, the temporal evolution of the following parameters was monitored:

- Water content and density;
- Atterberg limits (including I_c);
- Salt content;
- Organic content;

- Grain size distribution;
- Thickness and volume of drying mud;
- EC and pH of drained water from bottom drainages;
- Weather data;
- Groundwater table;
- Water quality of groundwater and ditches;
- GHG emission.

For future projects, it is advised to also monitor:
- Crack and crust development using a camera;
- Shrinkage and swelling behaviour of soil throughout the project;
- Water retention behaviour of soil throughout the project;
- Permeability of soil throughout the project.

Visual impressions from different phases of the pilot are presented below.

Figure 6 Visual impressions from the Clay ripening pilot in various stages of the project